# Brain Electric Mechanisms of Modalities of Thinking

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# Dedication

I would like to dedicate this doctoral thesis to my parents, Reinhard and Elisabeth. I am most thankful for their love, wisdom, and support which truly paved the way for me to develop into the person who could enthusiastically pursue and diligently complete this work.

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Abstract

The present thesis describes the investigation of brain electric mechanisms of modalities of thinking.

Brain electric mechanisms refer to the spatio-temporal dynamics of electrical activity in the brain. These dynamics were assessed by non-invasive head-surface recordings via electroencephalography and quantified by the microstate analysis and the functional Independent Component Analysis.

Modalities of thinking refer to particular modes of mental representations. Three modes were distinguished: spatial visualization, object visualization, and verbalization. Three modality-related person parameters were assessed: self-reported thinking modality, modality-related ability, and visual-verbal cognitive style. Visual-verbal cognitive style was assessed by the Modality of Thinking Questionnaire (developed and evaluated for this thesis).

The experimental investigation of the interrelationships between brain electric mechanisms and modalities of thinking revealed effects of modality-related tasks on, and associations of person parameters with brain electric activity. Tasks induced alpha decreases in modality-specific pathways, likely reflecting decreased inhibition of the network required to execute the task. Style and ability were related with alpha increases in modality-specific pathways, presumably reflecting increased automated processing (neural efficiency) in frequently applied networks. Longitudinal studies need to specify the causal direction of these interrelationships.

## Zusammenfassung

Die vorliegende Arbeit beschreibt die Untersuchung hirnelektrischer Mechanismen bezüglich sogenannter Modalitäten des Denkens.

Als hirnelektrische Mechanismen werden räumlich-zeitliche Veränderungen der elektrischen Aktivität des Gehirns bezeichnet. Diese Veränderungen wurden mittels Elektroenzephalographie aufgezeichnet und mittels Mikrozustandsanalyse und funktioneller Unabhängigkeitsanalyse quantifiziert.

Modalitäten des Denkens sind Formen mentaler Repräsentationen. Drei Formen wurden unterschieden: Räumliche Visualisierung, Objekt Visualisierung und Verbalisierung. Drei modalitätsbezogene personen-spezifische Masse wurden untersucht: berichtete Denkmodalität, modalitätsbezogene Fähigkeiten und visuell-verbaler kognitiver Stil. Letzterer wurde mit Hilfe des für diese Arbeit entwickelt und evaluierten ‘Modality of Thinking Questionnaire‘ erfasst.

Das Experiment dieser Arbeit zeigte Effekte Aufgaben-induzierter Modalität auf und Zusammenhänge personen-spezifischer Masse mit hirnelektrischer Aktivität. Modalitätsbezogene Aufgaben führten zu Alpha Reduktionen in modalitätsbezogenen Netzwerken, ein Ausdruck verringerter neuronaler Hemmung in zur Aufgabenbearbeitung relevanten Regionen. Stil und Fähigkeiten gingen mit Alpha Erhöhungen in Regionen der korrespondierenden Modalität einher, ein Ausdruck verstärkter automatischer Verarbeitung (neuronaler Effizienz) in häufig genutzten Netzwerken. Langzeitstudien sind notwendig um die Kausalität dieser Zusammenhänge zu klären.

Glossary

**BA:** Brodmann Area

**EEG**: Electroencephalography

**eLORETA**: exact Low Resolution Brain Electromagnetic Tomography (later version of LORETA)

**fICA**: functional Independent Component Analysis

**fMRI**: functional Magnetic Resonance Imaging

**GFP**: Global Field Power

**ICA**: Independent Component Analysis

**LORETA**: Low Resolution Brain Electromagnetic Tomography

**MOTQ**: Modality of Thinking Questionnaire

**Object visualization**: the act of mentally creating detailed visual images that strongly resemble perceivable objects

**OSIVQ**: Object-Spatial Imagery and Verbal Questionnaire

**rTMS**: repeated Transcranial Magnetic Stimulation

**Spatial visualization:** the act of mentally creating schematic images and representing spatial relationships between objects

**TANOVA**: Topographic Analysis of Variance

**Verbalization**: the act of internally speaking

**Verbalizer**: individual who tends to represent information verbally

**Visualizer**: individual who tends to represent information visually

**VVIQ**: Vividness of Visual Imagery Questionnaire

# 1. Introduction

## 1.1 Modalities of Thinking

This section describes what modalities of thinking are, how they are embedded in the greater context of cognitive styles, how their investigation developed historically, why they are considered relevant, and how they develop ontologically. Furthermore, visual-verbal cognitive style is considered in particular with regard to conceptualization, assessment, and interrelationships with personality and modality-related abilities.

This thesis is concerned with the question how individuals think. The form or mode of mental representations can be conceptualized in various ways. One distinction of particularly long history in psychological research is the distinction between visual and verbal mental representations. Since visual and verbal mental representations are closely related to two sensory modalities, sight and hearing (of speech), and since internal mental representations are referred to as thoughts in popular speech, I refer to these categories as modalities of thinking.

The distinction between visual and verbal mental representations reaches far back to the end of the 19th century. In 1883, Sir Francis Galton interviewed 100 adults about the nature of their mental representations. His inquiry was primarily concerned with the quality of mental images elicited by particular questions (Galton, 1883). For example, he asked what individuals had eaten for breakfast that morning and inquired whether this question elicited a mental image and if so, what its quality and content was. Interestingly, he found that some individuals have an "over-ready perception of sharp mental pictures", whereas others experience "highly generalized and abstract" thoughts in which "steps of reasoning are carried on by words as symbols" (Galton, 1883, p. 60). In the years to come, the nature of mental representations became a popular field of scientific investigation and debate. One line of research aimed to determine whether individuals think in images (e.g. the model of visual mental imagery by Kosslyn, 1980, 1996) or in image-unrelated categories (e.g. the propositional model by Pylyshyn, 1973), whereas another line of research aimed to classify individuals based on whether they think in images or in words (e.g. Paivio, 1971; A. Richardson, 1977).[1]

The advances in cognitive psychology and neuroscience of the past decades suggest that individuals are indeed capable of thinking both in images and words. However, the degree to which they rely on visual or verbal representations depends on several factors. These factors include age (e.g. Bruner, 1964; Piaget & Inhelder, 1969), context (e.g. the task to be solved: Riding & Cheema, 1991), modality-related cognitive style (e.g. visual-verbal cognitive style: Kraemer, Rosenberg, & Thompson-Schill, 2009), and modality-related abilities (e.g. mental imagery abilities: Blazhenkova & Kozhevnikov, 2009; Cui, Jeter, Yang, Montague, & Eagleman, 2007; Hegarty & Kozhevnikov, 1999).

The aim of this thesis is to uncover the interrelationships between modalities of thinking and brain electric mechanisms. Consequently, it must consider that individuals have an intrinsic propensity to use one modality over the other, an intrinsic ability to process information in these modalities, and that their mental representations can also be affected by external factors, including tasks that require individuals to solve particular modality-related problems. Thus, this thesis investigates task-induced and spontaneous thinking modalities and their interrelations with modality-related abilities and cognitive styles.

Visual imagery tasks and verbalization tasks can be used to induce thinking in these modalities. Self-report ratings on perceived visual and verbal processing can be used to assess spontaneous thinking modality. Reliable and valid cognitive tests can be used to assess modality-related abilities. Tests that distinguish between spatial-visual and verbal abilities were developed in great number under the topic of multiple intelligences (e.g. Gardner, 2011; Guilford, 1967; Jäger, 1982; Spearman, 1928). Tests that assess object-visual abilities were specified and applied more recently based on the

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[1] In 1971, Paivio proposed the dual coding theory in which he distinguishes between two representational systems: verbal and imaginal. He later (Paivio, 1978) referred to these two as “logogen” (word generator) and “imagen” (image generator) to distinguish their “underlying structural representation” from their inner perception as images or speech (Paivio, 1991, p. 258). Paivio (1991) further emphasizes that in his theory, imaginal representations are not limited to visual images, and verbal representations are not to be mistaken for propositional representations.

new emphasis on the distinction between spatial-visual and object-visual abilities (e.g. Blajenkova, Kozhevnikov, & Motes, 2006; Blazhenkova & Kozhevnikov, 2009).

However, the assessment of modality-related cognitive style, also referred to as visual-verbal cognitive style, is less straight-forward. A multitude of assessment measures have been proposed. However, these assessment measures and the investigation of cognitive style in particular have been harshly criticized (see Cools, Armstrong, & Verbrigghe, 2014 for a review). Consequently, the following section focuses on what cognitive styles are, what visual-verbal cognitive style is in particular, and how it can be assessed.

### 1.1.1 Cognitive Style

#### *Definition and History*

Cognitive style refers to a number of psychological dimensions that represent consistencies in an individual's manner of acquiring, processing, and representing information (Ausburn & Ausburn, 1978; Kozhevnikov, 2007; Messick, 1976; Witkin, Goodenough, & Karp, 1967).

The history of cognitive style has been described in several recent reviews (e.g. Armstrong, Cools, & Sadler-Smith, 2012; Kozhevnikov, 2007; Kozhevnikov, Evans, & Kosslyn, 2014). They suggest that cognitive style research originates in the works of Galton (1883), James (1890), and Jung (1923) around the turn of the 20th century. The term cognitive style was first used by Allport in 1937. In the 1940s and early 1950s, early cognitive-style related studies identified robust inter-individual differences in the selection of strategies applied to tasks associated with object perception and categorization (Hanfmann, 1941; Klein, 1951; Klein & Schlesinger, 1951; Witkin, 1950; Witkin & Asch, 1948).

In the later 1950s and 1960s, mainstream cognitive psychology showed great interest in cognitive style research and generated a tremendous number of cognitive style dimensions (Kozhevnikov, 2007). These dimensions were conventionally regarded as one-dimensional bipolar constructs. Popular examples of such bipolar constructs were the "levelling-sharpening" dimension by Klein (1951) or the "field-dependent – field-independent" dimension by Witkin et al. (1954). The former distinguishes between individuals based on their preferred perception of the environment. Levelers obliterate perceptual differences, whereas sharpeners have a heightened sensitivity to them. The latter distinguishes individuals based on the degree to which their perception and decision making are affected by the field. The field refers to the social, visual environment or frame of a situation. The field-dependent individuals are strongly affected by the field, whereas the field-independent individuals are not.

From the 1970s until recently, interest in cognitive styles greatly declined in mainstream cognitive psychology. It shifted its focus to the examination of capacities and constraints common to all individuals. However, in the meantime cognitive style research gained popularity in two applied fields, business and management, and education (Kozhevnikov et al., 2014).

### *Relevance in Applied Fields*

The growing interest in these applied fields is not surprising given the large number of reports on the predictive power of cognitive style dimensions on abilities and behaviors relevant to these fields. They include effects of various style dimensions on team effectiveness, leadership skills, decision making, creativity, innovation, susceptibility to particular biases, risk perception (see Armstrong et al., 2012 for a review), learning success based on material presentation modality (e.g. Chen & Macredie, 2002; Ford & Chen, 2000), vocational choice (e.g. Witkin, Moore, Goodenough, & Cox, 1975), and academic success (e.g. Leo-Rhynie, 1985; Witkin et al., 1977; Zhang, 2002),.

Based on these and similar findings, cognitive styles were regarded as significant in a wide range of disciplines including career guidance, counseling, personnel selection, internal communications, and conflict management (Hayes & Allinson, 1994). However, these findings are based on a wide range of cognitive style measures beyond the visual-verbal dimension. Moreover, recent reviews and meta-analyses suggest that the proposed relationships may not be as firmly established as may be suggested by this list. This applies at least to particular sub-fields of cognitive style (Kozhevnikov et al., 2014; Pashler, McDaniel, Rohrer, & Bjork, 2008; Peterson & Meissel, 2015).[2]

[2] For example, in educational psychology, a prominent hypothesis is the matching hypothesis: students learn more efficiently when the method of teaching matches their cognitive style (Kozhevnikov et al. 2014). According to Pashler et al. (2008), this hypothesis expects a particular interaction between style, instructional method, and learning success. However, the evidence that this interaction exists is not sufficient and consequently the application of cognitive style measures in education hardly warranted

***Evidence for Cognitive Styles***

Studies from inter-individual differences and neuroimaging support the conceptualization of cognitive styles as distinct patterns of acquiring, processing, and representing information, (see Blazhenkova & Kozhevnikov, 2009; Kozhevnikov et al., 2014 for reviews). Studies from inter-individual differences revealed style-dependent patterns of cognitive task performance (e.g. Blajenkova et al., 2006; Miyamoto, Nisbett, & Masuda, 2006), and differences in the cognitive style profiles between groups of different professions, vocational choices, course choices, and degree program choices (Blazhenkova & Kozhevnikov, 2012). Studies from neuroimaging revealed associations between style and neuronal activation patterns in the presence and absence of performance differences (see Kozhevnikov et al., 2014 and Section 1.3 of this thesis for a review).

***Ontological Development***

A fundamental question is how cognitive styles develop. A recent review suggests that cognitive styles develop based on abilities and personality traits via individuals' interactions with their environment (Kozhevnikov et al., 2014). Four interwoven environmental layers are distinguished: the immediate familial, the educational, the professional, and the sociocultural (see also Kozhevnikov, 2013). Indeed, cognitive styles are reportedly associated with abilities, personality traits, and these environmental layers (Blazhenkova & Kozhevnikov, 2009; Entwistle & Ramsden, 1983; Hayes & Allinson, 1998; Riding & Wigley, 1997; Varnum, Grossmann, Nisbett, & Kitayama, 2008). However, longitudinal studies are needed to specify their causal relationship. At least some previous longitudinal studies suggest that education and profession choice may be affected by cognitive style rather than the other way around. Several studies reported predictive effects of cognitive style on occupational choices in children (see Witkin et al., 1975 for a review) and young adults (Witkin et al., 1977). In particular, later on in their academic career, students are more likely to switch to a more compatible domain when they started college in a degree program incongruent with their cognitive style (Witkin et al., 1977).

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(Pashler et al. 2008). Others suggest that research on education-related styles should consider alternative style outcome measure interactions and go beyond aiming for a simple validation of the matching hypothesis (Kozhevnikov et al. 2014).

Moreover, not all cognitive styles need to affect or be affected by abilities, personality, and environmental layers to the same degree. The decisive period of visual-verbal cognitive style development may be the period during which children learn how to speak. According to developmental psychology, infants' mental representations are initially dominated by the visual modality and complemented with verbal representations only once language and verbal symbolic skills have developed (Bruner, 1964; Piaget & Inhelder, 1969). According to a study by Hollenberg (1970), children's visual imagery ability is positively associated with the speed at which they learn objects' labels but negatively with the speed at which they acquire the concepts underlying these labels. Possibly, early individual differences in abilities related to visual imagery and concept formation pave the way for the formation of visual as opposed to verbal cognitive styles, respectively.

### 1.1.2 Visual-Verbal Cognitive Style.

***Definition***

The term cognitive style is composed of two components "cognitive" and "style". According to the Merriam-Webster Encyclopedia, cognitive refers to "of, relating to, or involving conscious mental activities (such as thinking, understanding, learning, and remembering)" and style refers to "a particular way in which something is done, created, or performed" (cognitive, n.d.; style, n.d.).

The definition of style suggests it to refer to a propensity to habitually or frequently do something in a particular manner. The propensity to do something habitually is different from doing something well (an ability) or enjoying to do something (a preference) (see also Antonietti & Giorgetti, 1992, 1998; Childers, Houston, & Heckler, 1985; Curry, 1983; Mayer & Massa, 2003; Paivio & Harshman, 1983)[3].

[3] Obviously, an individual who enjoys doing something in a particular manner may also be more likely to do it that way. However, that habit and preference / enjoyment must be distinguished becomes evident by the tremendous efforts that are often necessary to change dysfunctional habits or patterns (see for example psychotherapy, nutritional counselling). Many individuals would like to do most frequently what they enjoy the most but despite their efforts fail to do so. Moreover, doing most frequently what is most enjoyable may not necessarily have the most beneficial consequences. Consequently, the cognitive

The definition of cognitive suggests it to refer to a number of processes related to information processing. These processes can be arranged based on the stage of information processing at which they operate. They range from information perception, concept formation, and comprehension (understanding), to acquisition (learning), internal representations (thinking), memory (remembering), and decision-making. Cognitive style models have used these stages of information processing to specify for different cognitive styles, the stage of information processing at which they operate (Kozhevnikov, 2007; Kozhevnikov et al., 2014; A. Miller, 1987; Nosal, 1990).

Theoretically, a propensity towards visual or verbal processing could operate at any stage of information processing. However, in the literature visual-verbal differences were primarily associated with two stages: information acquisition and mental representation. Historically, acquisition-related style differences are referred to as learnings styles (Curry, 1983; Mayer & Massa, 2003; Pashler et al., 2008), whereas mental representation-related differences are referred to as cognitive styles (Ernest, 1977; Riding & Cheema, 1991).

Consequently, this thesis defines visual-verbal cognitive style as an individual's propensity to internally represent information in a visual or verbal format. A broader definition of visual-verbal cognitive style might include learning styles, since they could also be regarded as habits associated with a particular stage of information processing. In agreement with this latter perspective, a recent review suggests that cognitive and learning style are different labels for the same concept (Kozhevnikov et al., 2014).

However, the retention of distinct labels for learning style and cognitive style appears still appropriate for at least three reasons: (1) learning style refers to a different stage of information processing (acquisition vs. representation), (2) the term style in learning style is misleading, since learning style is defined as an individual's ability (also efficiency: Pashler et al., 2008) or preference (Jonassen & Grabowski, 2012) to acquire information in a particular modality rather than a habitual mode, and (3) empirical findings showed no or only low correlations between visual-verbal cognitive

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style literature emphasizes the distinction between habit / frequency and enjoyment (e.g. Antonietti & Giorgetti, 1992).

style with learning style and learning preferences (Kirby, Moore, & Schofield, 1988; Mayer & Massa, 2003; Sadler-Smith, 2001).[4]

The next section evaluates previous assessment measures based on the proposed definition of visual-verbal cognitive style that relates it to habitual mental representations.[5]

***Assessment***

Several measures have been developed to assess visual-verbal cognitive style. They include self-report questionnaires (Antonietti & Giorgetti, 1992; Blazhenkova & Kozhevnikov, 2009; Childers et al., 1985; Paivio, 1971; A. Richardson, 1977), objective tests (Peterson, Deary, & Austin, 2005; Riding, 1991), and observation and self-reports of strategies applied in particular testing situations (Antonietti & Giorgetti, 1992; Lean & Clements, 1981; Presmeg, 1986).

**Self-report questionnaires.** All existing self-report questionnaires suffer from at least one of three limitations: (1) they include items of questionable validity, i.e. they measure a construct other than visual-verbal cognitive style (for this criticism see also Antonietti & Giorgetti, 1992, 1998; Childers et al., 1985; Curry, 1983; Mayer & Massa, 2003; Paivio & Harshman, 1983), (2) they assess visual-verbal cognitive style based on an outdated bipolar model (for this criticism see also Antonietti & Giorgetti, 1992, 1998; Blazhenkova & Kozhevnikov, 2009; Edwards & Wilkins, 1981; McGrath, O'Malley, Dura, & Beaulieu, 1989; Paivio & Harshman, 1983), or (3) they lack a distinction between the spatial- and object-visual dimensions (for this criticism see also Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009; Hegarty & Kozhevnikov, 1999).

(1) The most frequently used items of questionable content validity assess (a) the self-report of a modality-specific ability, (b) the self-reported enjoyment of processing information in a particular modality, and (c) the preference to acquire information in a particular modality.

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[4] The conceptual difficulty is that several authors applied different definitions to the same labels (see also Riding & Cheema, 1991). Some refer to learning style as an ability (e.g. Pashler et al., 2009) others refer to it as a preference (e.g. Jonassen and Grabowski, 2012).

[5] Other assessment measures that assess different processing stages in which individuals may habitually differ with regard to visual or verbal processing are also conceivable but not the focus of this thesis.

(a) The use of items that assess the self-report of a modality-related ability implies that visual-verbal style is reflected by its corresponding ability. However, the conceptual differences between modality-related abilities and styles have repeatedly been emphasized in the literature (e.g. Antonietti & Giorgetti, 1992; Childers et al., 1985; Mayer & Massa, 2003; J. T. Richardson, 1978). Whereas abilities refer to “things that people are capable of doing”, styles refer to “ways that people process and represent information” (Mayer & Massa, 2003, p. 833). Styles are not only regarded as different from abilities, but even suggested to only add value to our understanding of individual differences if the number of overlaps with ability are few, their strength low and clearly documented (Peterson et al., 2005). Factor analyses showed that self-report of ability items of visual-verbal cognitive style questionnaires load higher on a factor shared with modality-related ability assessments than other cognitive style items (Childers et al., 1985). Consequently, the use of self-report of ability items to assess visual-verbal cognitive style has several problematic consequences. They lead to the assessment of a heterogeneous construct which, if regarded to reflect visual-verbal cognitive style, may suffer from the over-estimation of retest reliability, and the over-estimation of correlations with other variables including modality-related cognitive tests, the success in particular degree programs, or professions.

(b) The use of items that request the self-reported enjoyment of processing information in a particular modality is problematic because the fact that a person enjoys doing something does not inevitably lead them to pursue that activity habitually (see also: Antonietti & Giorgetti, 1992; Childers et al., 1985, and footnote 3).

(c) The use of items that assess the preference to acquire information in a particular modality are problematic because it implies that cognitive style and learning material modality preferences were the same. However, also their conceptual differences have been emphasized in the literature. Whereas learning preference refers to “ways that people like information to be presented to them”, cognitive style refers to “ways that people process and represent information” (Mayer & Massa, 2003). Based on a similar distinction, Curry (1983) proposed an “onion” model of individual difference constructs. In this model the central personality dimension is at the core, followed by cognitive style, learning style, and learning preferences. Increasing distances from the core were suggested to reflect increased openness to introspection, increased context-dependence, and decreased stability.[6]

(2) The assessment of visual-verbal cognitive style on one bipolar dimension implies that a person can be placed on a continuum between representing information visually and verbally. Consequently, the more visual an individual is the less verbal they are expected to be and vice-versa. This model has repeatedly been criticized in the literature based on theoretical considerations, as well as empirical evidence. Theoretical criticisms suggest that a person may think neither visually nor verbally (Antonietti & Giorgetti, 1992), and that visualization and verbalization may represent independent dimensions rather than extremes of the same dimension (Antonietti & Giorgetti, 1992; Blazhenkova & Kozhevnikov, 2009; Edwards & Wilkins, 1981; McGrath et al., 1989). Evidence for the latter comes from factor analyses of visual-verbal cognitive style measures and neuroscientific findings. The former revealed a two-factor rather than a one-factor structure of visual-verbal style measures (e.g. Paivio & Harshman, 1983). The latter suggest that visual and verbal processing is conducted by largely independent brain networks. This independence was suggested to provide no evidence that an individual who tends to internally visualize is unlikely to internally verbalize or vice-versa (see also Blazhenkova & Kozhevnikov, 2009 and Manuscript 1). The lack of unipolar assessment of the visual and verbal scales has two limiting effects. Firstly, it leads to the inability to distinguish between respondents with similarly high or low scores on both dimensions. Secondly, it leads to the inability to quantify the absolute differences between visual and verbal propensities within one and the same individual.

(3) The distinction between spatial- and object- visual with regard to visual-verbal cognitive style was introduced more recently (Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009; Hegarty & Kozhevnikov, 1999). It is based on reports from neuroscience, cognitive psychology, and inter-individual differences. Neuroscientific findings suggest that spatial-visual and object-visual processing have a largely distinct neuronal basis. Lesion studies suggest that double-dissociations between spatial-visual and object-visual processing are possible (some individuals are

[6] Learning preferences and learning style are also distinct constructs. Whereas the former refers to “ways that people like information to be presented to them” (Mayer and Massa, 2003, p. 833), the latter refers to the “mode of instruction or study most effective for them” (Pashler et al 2009, p. 105).

impaired for spatial-visual imagery only but not object-visual imagery, and vice-versa, see Bartolomeo, 2002; Bartolomeo, 2008 for reviews). Dual-task studies showed that performance on a spatial-visual task is impaired by an additional spatial but not object-visual task, and vice-versa (Bartolomeo, 2002, 2008). Studies from inter-individual differences showed that visualizers can be divided into two extreme groups based on their spatial-visual and object-visual abilities (Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009).

The lack of distinction between spatial and object visual reportedly impedes a clear association between visual style and visual abilities (Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009; Hegarty & Kozhevnikov, 1999). This is reflected by the multitude of confounding findings on the relationship between visual-verbal style and modality-related abilities when the visual dimension is not further divided (e.g. Alesandrini, 1981; Kirby et al., 1988; Kraemer et al., 2009; Lean & Clements, 1981; Mayer & Massa, 2003; Riding & Pearson, 1994).

The authors that noted the described problems developed new measures that excluded self-report of ability items (Antonietti & Giorgetti, 1992; Childers et al., 1985), used an equal number of items that assess "frequency / habit" and "liking / preference" (Antonietti & Giorgetti, 1992), assessed visual-verbal on single unipolar scales rather than a bipolar scale (Antonietti & Giorgetti, 1992), and distinguished a spatial-visual from an object-visual style dimension (Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009). However, none of these improved questionnaires addressed all three problems simultaneously (see Table 1).

*Table 1*

Limitations of Questionnaires of Visual-Verbal Cognitive Style

| Publication | Questionnaire | Validity | Bipolarity | Visual One-Dimensionality |
|---|---|---|---|---|
| Paivio (1971) | Individual Differences Questionnaire | yes | (yes[1]) | yes |
| Richardson (1977) | Verbalizer Visualizer Questionnaire | yes | (yes[1]) | yes |
| Childers et al. (1985) | Style of Processing Scale | yes | (yes[1]) | yes |
| Antonietti and Giorgetti (1992) | The Coding Preference Questionnaire | no | no | yes |
| Blazhenkova and Kozhevnikov (2009) | Object-Spatial Imagery and Verbal Questionnaire | yes | (yes[2]) | no |

*Note.* Validity refers to the assessment of a heterogeneous construct beyond habitual mental representations. Bipolarity refers to the assessment of visual-verbal on one dimension or usage of items that enforce bipolarity. Visual One-Dimensionality refers to the assessment of the visual dimension without a distinction between spatial-visual and object-visual aspects. (yes[1]) refers to scales that were typically scored on a single value as a relative preference but two dimensional scoring would be possible. (yes[2]) refers to scales in which separate dimensions are available but include forced choice items that ask respondents to decide between dimensions. The list of questionnaires is not exhaustive. Several assessment measures that are related to visual-verbal cognitive style but assess (also) other dimensions are not listed (e.g. Sensory Modality Preference: Bartlett, 1932; Your Style of Learning and Thinking Questionnaire: Torrance, Reynolds, Ball, & Riegel, 1978).

**Objective tests.** Beyond the limitations mentioned with regard to these particular questionnaires, self-report measures suffer from well-known limitations simply because they rely on self-reports (Amelang & Schmidt-Atzert, 2006; Choi & Pak, 2005). Consequently, alternative objective assessment approaches of visual-verbal cognitive style would be very desirable. An example of such an assessment measure is the visual-verbal dimension of the Cognitive Style Analysis (CSA: Riding, 1991). The CSA is a computerized test that assesses an individual's position on the visual-verbal cognitive style dimension by computing the ratio of their reaction time to questions about a visual category (color: "Are blood and tomato of the same color?") versus a semantic category (same type: e.g. "Are car and van of the same type?"). The computation of the visual-verbal score is based on the following assumptions: Visualizers tend to represent information visually, thus may automatically visualize an object when presented with its label. This automated visualization may be the quickest way to retrieve an answer to the color question. Verbalizers tend to represent information verbally. Thus, they may have conceptual categories more accessible and consequently be faster at retrieving an answer to the semantic category question.

Due to reports on the poor reliability, the CSA (Peterson, Deary, & Austin, 2003) was revised and modified. This revised version is referred to as Verbal-Imagery Cognitive Style Test (VICS) (Peterson et al., 2005). The VICS modified the CSA by altering the types of questions asked. Rather than asking about whether two objects are of the same color, or type, they ask about which of two items are "bigger in real life" and whether they are “man-made” or “natural”. They further present an equal number of items as words and as images. These changes to the test improved reliability (internal consistency: r>.71; retest: r=.56 as compared to .03 and .31 for the CSA).

Despite this improvement in reliability, the validity of the CSA and VICS remained questionable (see also: Blazhenkova & Kozhevnikov, 2009). It is not evident why the relative speed of answering questions related to an object’s color or size as opposed to an object’s semantic type or naturalness would need to be associated with an individual’s propensity to represent information visually as opposed to verbally, respectively. It may not be necessary to internally visualize to answer a color or object-size related question. Alternative verbal or otherwise non-visual strategies are conceivable. It is not evident why they would need to be associated with slower response times. Moreover, some individuals may be very flexible at varying strategies task-dependently (Niaz, 1987). This may reflect in very small response time differences, which again may not be related to individuals’ habitual modes of internal representation.

Furthermore, the CSA and VICS lack the distinction between spatial visual and object visual. Consequently, it is not surprising that it reportedly fails to predict performance on spatial tasks (see also: Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009; Lean & Clements, 1981; Massa & Mayer, 2006).

**Strategies applied in particular testing situations.** A third approach to identify an individual’s visual-verbal cognitive style investigates the strategy of individuals applied to problem solving. Several strategies of observation have been applied: evaluating participants’ drawings or writings on paper as they solve the problems (e.g. Moses, 1980), asking participants to verbalize their strategy as they use it (e.g. Presmeg, 1986), or asking participants in retrospect about which strategy they had just applied (e.g. Antonietti & Giorgetti, 1992; Hegarty & Kozhevnikov, 1999; Krutetskii, Wirszup, & Kilpatrick, 1976; Lean & Clements, 1981; Presmeg, 1986).

Based on such investigations, Presmeg (1986) identified a list of strategies related to visual and verbal processing. These strategies included concrete pictorial imagery, pattern imagery (schematic spatial relationships), kinesthetic imagery (involving gestures), dynamic imagery (involving transformations of figures), and memory of formulas (e.g. written on a blackboard). Concrete pictorial imagery was later associated with object visualization, and pattern imagery with spatial visualization (Blajenkova et al., 2006; Hegarty & Kozhevnikov, 1999). However, this strategy list suggests that there may be additional types of imagery applied during problem solving that have not been considered with regard to visual-verbal cognitive style assessments.

Despite very enlightening and useful for hypothesis generation, these strategies of observing individuals during problem solving to determine their cognitive style also suffer from several limitations. An individual's strategy to solve a problem / task in a particular manner may depend on several factors including the task, their ability to adapt to a given task (Niaz, 1987), the instructions presented prior to the task (e.g. draw, write, speak out loud), and more (see also: Lean & Clements, 1981). With regard to habitual modes of mental representations, the observation that an individual applied a particular visualization strategy in a particular number of mathematical tasks does not imply that they habitually represent information with the same strategy on a day to day basis. On a day to day basis, individuals are faced with various situations and various problems that may be quite distinct from the ones presented in an experimental setting.

**Conclusion on cognitive-style assessment.** The review of the literature on the definition and assessment of visual-verbal cognitive style led me to four conclusions: First, visual-verbal differences may affect different steps of information processing that may or may not be related and thus should be assessed separately.[7] Second, there is a certain agreement that visual-verbal cognitive style refers to habitual modes of applying visual or verbal mental representations, whereas learning style refers to the ability to acquire information in a visual or verbal format. Third, visual-verbal cognitive style is most directly accessible by self-report questionnaires, since objective measures rely on many assumptions, which are hard to prove, and observations during problem solving may lack external validity. Fourth, visual-verbal cognitive style self-report questionnaires profit from avoiding items of questionable validity, and assessing style on three unipolar dimensions that distinguish between spatial-visual, object-visual, and verbal style.

Based on these conclusions, we developed the Modality of Thinking Questionnaire (Manuscript 1). To my knowledge, the MOTQ is the first questionnaire

[7] Theoretically, an individual may tend to acquire information in a verbal format but then tend to convert this information to an image. Such a discrepancy between the frequent mode of acquiring and representing may be beneficial. This is suggested by the literature on working memory that suggests that the availability of more than one code of representation can improve information retrieval (see also Kraemer et al., 2009).

which avoids the three limitations of previous self-report questionnaires simultaneously.

***Associations with Ability and Personality***

According to the literature, cognitive style may represent "a bridge between what might seem to be two fairly distinct areas of psychological investigation: cognition and personality" (Sternberg & Grigorenko, 1997, p. 701). Consequently, the relationship between cognitive style, personality, and ability has been investigated in several studies. The results of these studies were very heterogeneous.

With regard to personality, some studies revealed no associations between visual-verbal cognitive style with personality dimensions (e.g. Peterson et al., 2005), whereas others reported associations with extraversion, inwardness, detachedness, seriousness, and patience, in various age groups (see Riding & Cheema, 1991; Riding & Wigley, 1997 for reviews).

Similarly, with regard to ability, some studies revealed no associations between visual-verbal cognitive style with modality-related abilities (Alesandrini, 1981; Hiscock, 1978; Kraemer et al., 2009; Lean & Clements, 1981; Peterson et al., 2005), others found low to moderate positive correlations (Blazhenkova & Kozhevnikov, 2009; Ernest, 1979; Hiscock, 1978; Hollenberg, 1970; Kirby et al., 1988; A. Richardson, 1977). Again others found counter-intuitive associations such as higher spatial-ability for verbalizers than visualizers (Lean & Clements, 1981) or better recall of images for verbalizers than visualizers (Childers et al., 1985).

Both positive correlations and a lack of correlations with style were interpreted as evidence for the validity of the respective assessment measure (Blazhenkova & Kozhevnikov, 2009; Peterson et al., 2005; J. T. Richardson, 1978; Riding & Wigley, 1997). The lack of consistency of visual-verbal cognitive style measures with modality-related abilities were also associated with the limitations of previous assessment measures (see also: Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009; Ernest, 1979; Hegarty & Kozhevnikov, 1999).

From a theoretical standpoint, low to moderate correlations between the two visual style dimensions are to be expected for a simple reason. It is unlikely that an individual who is not able to create spatial- and object-visual internal representations will do so habitually. However, this reasoning only applies to the spatial- and object-visual dimension, if spatial- and object-visual ability are assessed with measures that demand an individual’s ability to process information in the respective format (e.g. to create spatial images or detailed images, respectively). This reasoning does not apply in the same manner to the verbal dimension, since verbal ability tests measure something other than the ability to think in words. They measure verbal fluency, sophistication, vocabulary, or grammatical correctness. However, for internal verbalization it is only necessary to be able to lead an internal monologue / dialogue regardless of its quality or level of sophistication.

These considerations simply suggest that to score high on verbal abilities is no prerequisite for frequent mental verbalization. However, it can be speculated that modality-related style and abilities may also correlate for a different reason. Namely, frequent application of mental representations in a particular modality may strengthen neural pathways and thus lead to more efficient processing. This increased efficiency may in turn reflect in higher modality-related abilities.

Manuscripts 1 and 3 report results that contribute to the clarification of the interrelationship between visual-verbal cognitive style and modality-related abilities. Manuscripts 2 and 3 describe their brain electric correlates.

## 1.2 Brain Electric Mechanisms

This section describes what brain electric mechanisms are, how they can be measured and how they can be analyzed.

Brain electric mechanisms can be measured by electroencephalography (EEG). EEG is a non-invasive method where electrodes are placed on the human head-surface at pre-defined positions (e.g. Chatrian, Lettich, & Nelson, 1985; Nuwer, 1987). These electrodes are used to detect electric potential changes generated by neurons of the brain in the range of millivolts and milliseconds. The potential changes result from ionic currents primarily generated by large populations of simultaneously active neurons. The head-surface EEG recordings are particularly sensitive to neural activity located in the cortex, especially crests of gyri when they are oriented radially to the skull (Niedermeyer & da Silva, 2005). These requirements are fulfilled by the pyramidal neurons of cortical layers II/III and V which extend apical dendrites to layer I (Murakami & Okada, 2006). Therefore, their activity has been suggested to contribute most strongly to the EEG signal. However, also subcortical activity can be detected via EEG measurements when their magnitude is strong enough (e.g. epileptic spikes: Federico, Archer, Abbott, & Jackson, 2005) or the signal is post-processed via averaging procedures on repeated event-related recordings (e.g. evoked potentials: R. D. Miller, Eriksson, Fleisher, Wiener-Kronish, & Young, 2010).

Multichannel EEG recordings can be analyzed in various ways (Michel, Koenig, Brandeis, Gianotti, & Wackermann, 2009). Popular analysis methods include the EEG spectral power analysis in which the occurrence and magnitude of activity in particular frequency ranges are quantified, the EEG source analysis in which head-surface recordings are recomputed into activity in intra-cerebral sources, and the EEG microstate analysis in which time-frame wise head-surface topographies of electric maximal positivity and negativity are inspected across time (Lehmann, Ozaki, & Pal, 1987; Lehmann & Skrandies, 1980).

This thesis applied three EEG analysis approaches: the EEG spectral analysis (Unpublished Results), the EEG microstate analysis (Manuscript 2), and the functional independent component analysis based on exact Low Resolution Brain Electromagnetic Tomography (eLORETA) (Manuscript 3). The first analysis was performed for illustration purposes and validation with the previous literature that used this approach. The latter two analysis approaches have complementary advantages and disadvantages and thus were expected to provide a more thorough view of the obtained EEG data (Data Assessment 3) that neither could have provided on its own.

The EEG microstate analysis relies on the analysis of the head-surface topographies of EEG activity in a broad frequency band which is minimally affected by muscular artifacts. Thus, it has the following advantages over other methods. (a) The direct inspection of head-surface activity does not rely on the physical and physiological assumptions necessary for source analysis. (b) The analysis of the topography of potential distributions is independent of the choice of reference[8] (Lehmann et al., 1987; Lehmann & Skrandies, 1980). (c) The signal is not divided into frequency bands. Thus, it does not rely on the assumption that the EEG signals'

[8] In EEG research, the choice of optimal location or computation of the reference for EEG signals has been a matter of debate. Divergent choices have led to an extensive amount of diverging results (Geselowitz, 1997). The diverging results are due to the decisive effect of the choice of reference on the wave form of the EEG signal and thus its spectral components and the degree of statistical covariation between signals from various channels. The EEG microstate analysis elegantly avoids this problem because whereas the wave form changes with varying references, the topography remains the same (Lehmann et al., 1987).

physiological function is frequency-dependent and it avoids the problem that the physiologically useful frequency band borders may vary across individuals (e.g. Klimesch, Sauseng, & Gerloff, 2003).

The eLORETA functional independent component analysis relies on the analysis of source-localized EEG in discrete frequency bands and the degree of covariation of cross-frequency activity across participants and / or time. Thus, it relies on the assumptions associated with this particular inverse solution and it relies on the assumptions associated with frequency band divisions. To take these assumptions into account is warranted by the studies that validated the accuracy of the LORETA source-localization (Pascual-Marqui, 1999, 2007; Pascual-Marqui et al., 2011; Takahashi et al., 2013) [9], and the consistent frequency band borders derived across individuals from independent component analyses (Kubicki, Herrmann, Fichte, & Freund, 1979; Niedermeyer & da Silva, 2005). The advantage of the source localization is that it allows the specification of the intracortical sources of the EEG activity. The advantage of dividing EEG activity into activity in different frequency ranges is that the results retrieved from such an analysis can profit from the knowledge on the EEG frequency bands' empirically derived physiological functions (e.g. Gevins, Smith, McEvoy, & Yu, 1997; Klimesch, 1999; O'Gorman et al., 2013; Pfurtscheller & Da Silva, 1999). The additional step of applying independent component analysis to the data has at least two additional advantages. First, it allows the detection of spatially distributed cross-frequency brain networks rather than simply brain areas of increased or decreased activation between conditions and / or individuals. Second, it allows the decomposition of the EEG signal into physiological signals and artifact signals which can be identified via their spatial power distributions and frequency ranges (e.g. Aoki et al., 2015).

The two analysis approaches are described in detail in the two manuscripts (Manuscript 2 and 3) of this thesis. The following sections give a short intuitive understanding of the idea behind the analyses and the software available for their application.

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[9] The LORETA source-localization is also reference-independent (see Pascual-Marqui, 2007 for mathematical proof, see Ruchkin, 2005 for the suggestion to apply source-localization to avoid the reference problem).

### 1.2.1 EEG Microstate Analysis

***Procedure***

The EEG microstate analysis is based on an intriguing discovery made by Dietrich Lehmann in the early 1970s (D. Lehmann, personal communication, December 11, 2012). He inspected, by eye, millisecond by millisecond, consecutive topographic maps of the potential distribution of spontaneous EEG brain electric activity. After having inspected countless maps, he realized a remarkable pattern. The EEG's potential distribution remains quasi-stable for a relatively long period of time (roughly 100 ms) to then abruptly change to a different distribution which again remains quasi-stable for a relatively long period of time. This pattern turned out to repeat itself over and over across long periods of spontaneous EEG, and to reappear consistently across different assessment time points and individuals.

Based on this discovery, together with co-workers, he developed the EEG microstate analysis (Lehmann, 1971; Lehmann et al., 1987; Lehmann & Skrandies, 1980). The EEG microstate analysis aims to identify the time sequences of these stable topographies, to then be able to investigate their topographical differences, duration, occurrence, coverage, and sequence / syntax. These stable topographies are referred to as EEG microstates.

Since the 1970s, this analysis has been applied to event-related potential changes as well as spontaneous EEG. The methods used to identify the EEG microstates' topographies and the time segments during which they are prominent underwent several steps of refinement (Lehmann, 1971; Lehmann & Skrandies, 1980, 1984; Michel, Seeck, & Landis, 1999; Pascual-Marqui, Michel, & Lehmann, 1995; Strik & Lehmann, 1993; Wackermann, Lehmann, Michel, & Strik, 1993). For example, originally, EEG microstates were identified sequentially (e.g. Lehmann, Strik, Henggeler, Koenig, & Koukkou, 1998), later with cluster analytical approaches (e.g. Pascual-Marqui et al., 1995). Also the analysis of the EEG microstates' topography, temporal parameters, and sequence / syntax were refined (Brunet, Murray, & Michel, 2011; Gärtner, Brodbeck, Laufs, & Schneider, 2015; Kikuchi et al., 2011; Lehmann, Faber, Galderisi, Herrmann, Kinoshita, Koukkou, Mucci, Pascual-Marqui, Saito, Wackermann, et al., 2005; Van de Ville, Britz, & Michel, 2010). Originally, the frequency of changes of a particular topography to another were directly quantified and compared, more recently Markov chain models (Gärtner et al., 2015) investigate sequence probabilities and long-range dependencies investigate sequence patterns across larger time segments (Van de Ville et al., 2010).

A most interesting discovery resulted from the inspection of EEG map topographies based on cluster analytical approaches. Approximately 80% of the variance of spontaneous resting state EEG can be explained by only four EEG microstate map topographies (Koenig et al., 2002; Wackermann et al., 1993). These four topographies have consequently been labeled from A to D and are conventionally referred to as EEG microstate classes (Koenig et al., 2002). A recent study identified the intra-cortical sources of these four microstate classes. Interestingly, they overlap with the core hubs of the default mode network (Pascual-Marqui et al., 2014). Another recent study suggested that the four EEG microstate classes A, B, C, and D may be associated with four distinct functions, phonological, visual, autonomic self-referential processing, and attention-reorientation (Britz, Van De Ville, & Michel, 2010). These associations were suggested based on correlations of the four classes during resting with fMRI networks retrieved from simultaneously obtained fMRI data. The fMRI networks had previously been associated with the four identified functions. Manuscript 2 tests whether these hypothesized functions of the four microstate classes can be validated via experimental manipulation of the processing demand on these functions.

***Implementation***

In recent years, the EEG microstate analysis gained increasing popularity in academic quantitative EEG research (Khanna, Pascual-Leone, Michel, & Farzan, 2015; Minguillon et al., 2014; Schwab et al., 2015). Many researchers are interested in easy-to-use software packages to apply the EEG microstate analysis to their own datasets. At the KEY Institute for Brain-Mind Research, we receive frequent inquiries on how to conduct an EEG microstate analysis properly. Moreover, over the past years, researchers from all over the world have visited our institute to learn about the application and interpretation of the EEG microstate analysis.

There are several existing software applications that implement versions of EEG microstates analysis algorithms for spontaneous and / or event-related EEG data (e.g. Cartool: Brunet et al., 2011; RAGU: Koenig, Kottlow, Stein, & Melie-García, 2011; LORETA: Pascual-Marqui, 2002). These applications are all available for free and integrate manuals and documentations. Although many of these packages have user-friendly graphical user interfaces, the amount of inquiries we receive suggests that many researchers still struggle to find, apply them, or at least need additional support. Moreover, some of these software applications are closed source and therefore not modifiable. Another disadvantage is that they require user-interaction for analysis. This is a major obstacle to perform automated analyses of large EEG datasets with many participants based on varying parameter configurations.

Python is an easily accessible, scriptable programming language that has gained increasing popularity in academia over the past few years (Guo, 2014; Piatetsky, 2013). Its popularity has been associated with a large ecosystem of supporting scientific computing libraries (e.g. NumPy, SciPy, pandas, matplotlib), interactive programming (IPython), high productivity (efficient prototyping and building small, reusable systems), and its wide applications (McKinney, 2012). The Python interpreter and library are freely available for all major platforms and operating systems. Python-based scientific software applications are particularly successful when they integrate means for users to modify their own analysis (Gerhard et al., 2011).

For these reasons, I developed the KEY EEG Python Library (keypy). It is an open-source library freely available on Github for download, modification, and extension under the GPL 3-Clause license. In addition to algorithms for preprocessing, spectral analyses, and LORETA post-processing, its core functionality is a set of routines that allow the computation of EEG microstates and their statistical analysis. The novice user can adjust a simple sample script that preprocesses the data, computes the EEG microstate maps for each EEG time segment, computes means across maps (referred to as modelmaps), sorts these maps (for example, based on the normative four microstate classes by Koenig et al., 2002), computes the EEG microstate parameters based on the sorted maps, and performs the subsequent statistics that test for differences between groups of participants or conditions. The advanced user can choose between different computation options, and modify and extend any parts of the algorithms.

Figure *1* shows the workflow of the microstate analysis implemented in the keypy library. Figure 2 shows three of the several possible options of microstate class computations based on the microstates of individual participants. The complete list of the currently implemented functions can be found on https://github.com/keyinst/keypy.

The purpose of sharing with the EEG community the algorithms necessary to perform the EEG microstate analysis is to facilitate other researchers to contribute to the knowledge on the temporal dynamics and the functional significance of the EEG microstates discovered by Professor Dietrich Lehmann (Lehmann et al., 1987).

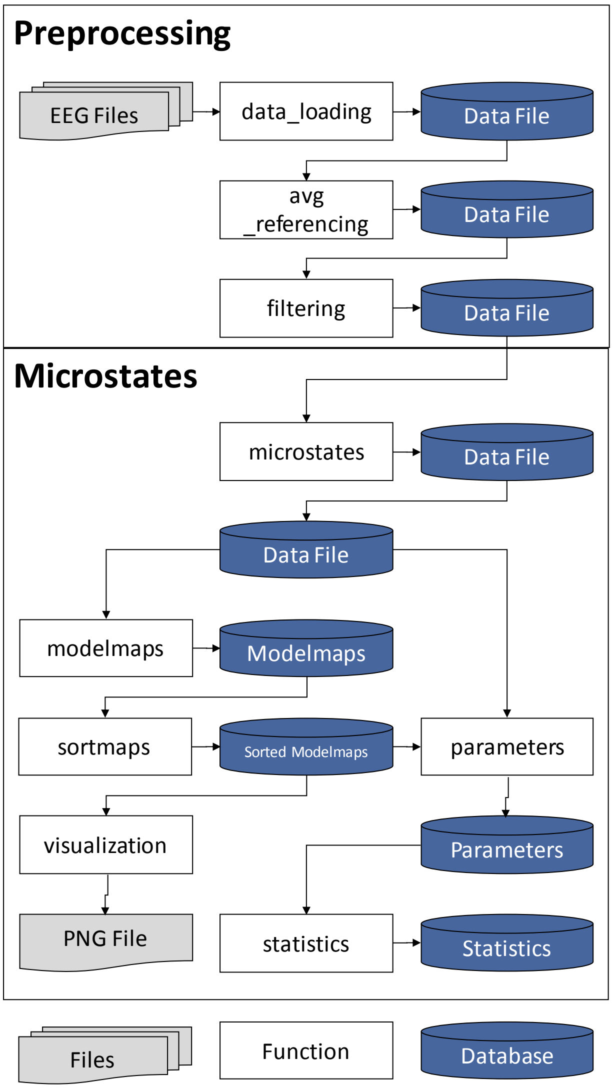


*Figure 1.* Microstate analysis workflow.

data_loading loads EEG data files into an hdf5 data file. The folder structure and / or naming convention can be specified. The data_loading function automatically creates the hdf5 file in a group, participant, condition, run –type hierarchy. For each run, the inputted data is saved in a separate dataset (e.g. rawdata). These raw data can then be re-referenced to average reference (avg_referencing). They can then be filtered (filtering), and EEG microstates can be computed (microstates). The final hdf5 file contains a separate data file for each processing stage.

Mean microstate classes (modelmaps) can be computed across runs, conditions, participants, and / or groups. Modelmaps can be sorted (sortmaps) according to a requested hierarchy level. Sorted maps can be visualized or used to compute EEG microstate parameters (parameters: duration, occurrence, and coverage, explained variance). Parameter-based statistical analyses can also be computed (statistics).

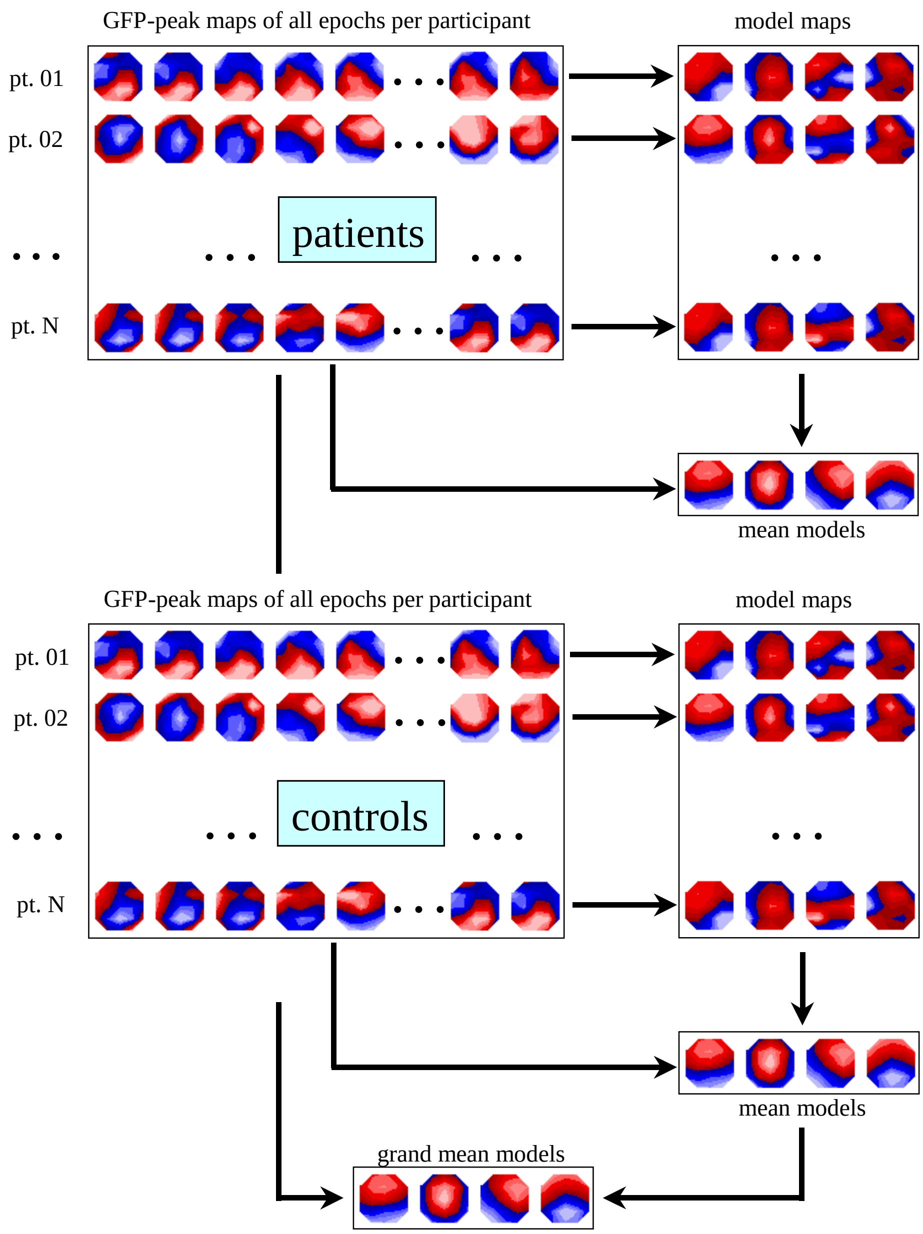


*Figure 2.* Modelmaps options.

Three of the options implemented in keypy to obtain grand mean models (averages across participants) from the global field power peak (GFP) maps of participants (pt.). Illustration edited from original by P.L. Faber.

### 1.2.2 eLORETA Functional Independent Component Analysis

***Procedure***

The eLORETA functional independent component analysis (fICA) was first described by Pascual-Marqui and Biscay-Lirio (2011) and first applied by Aoki et al. (2015). It combines the decomposition of the EEG signal into frequency-bands, their source-localization, and the independent component analysis of these data.

Thus, it is comprised of three parts (see also Aoki et al., 2015 and Manuscript 3). First, artifact-free segments of EEG of a particular duration (e.g. two seconds) are decomposed into cross-spectral density matrices of a number of EEG frequency bands. Second, based on the information of the location of each EEG signal on the scalp, these matrices are used to estimate the spectral power of electric neuronal activity in 6239 cortical grey matter voxels for each EEG frequency band. Third, these frequency band-wise images are subjected to an independent component analysis (ICA). Each of them contains spectral power values for each voxel.

This ICA reveals independent components (factors), their eigenvalues, and the loadings of these factors for each image entered into the analysis. The variance of each image can be explained (with a particular error depending on the variance explained by all factors) by the sum of products of each loading (also referred to as mixing coefficient) with its corresponding factor. These loadings vary between individuals and across epochs within the same individual. Brain networks differentially activated between states can be identified as follows. Loadings obtained during one mental state are averaged and compared to the average obtained from another mental state.

This analysis is termed functional independent component analysis because unlike ICA applied to fMRI images, the data entered into the analysis is not limited to spatial information across time / or participants but extends to frequency-band-wise spatial information across time / or participants. These frequency-bands have been associated with particular functions (Bazanova & Vernon, 2014; Harmony, 2013; Niedermeyer & da Silva, 2005; O’Gorman et al., 2013; Palva & Palva, 2007; Pfurtscheller, 2003; Pfurtscheller & Da Silva, 1999). Consequently, *functional* here refers to this additional distinction.

The only previous study which used this method (Aoki et al., 2015) used one image (frequency-band-wise values for each voxel) for each participant during eyes closed resting. The study described in Manuscript 3 aimed to capture cross-frequency networks that may only be active at particular times during a longer spontaneous EEG recording. These may average out when only one image is used across this longer time period. Therefore, we decomposed the networks based on a large number of two-second EEG epochs. Beyond resting, we also used tasks to induce differential activities in these networks.

***Implementation***

The eLORETA fICA is fully implemented in the LORETA software package developed by Dr. Roberto Pascual-Marqui which is freely available at: http://www.uzh.ch/keyinst/loreta. To apply it, users must artifact-correct their EEG data and segment it into equal-length segments of EEG epochs. The EEG data must be in the format time frames by channel number. Users also need a list of the electrode names in the same order as in the EEG files. Then users can transform their channels' names into electrode coordinates. These electrode coordinates can in turn be used to retrieve a transformation matrix which is necessary for the source-localization procedure. The EEG data needs to be recomputed into EEG cross spectra, and then into eLORETA images. These eLORETA images can in turn be directly subjected to fICA. Various means of scaling (e.g. subject-wise, frequency-wise) are available. The output of the analysis comprises several files. They include general information on the fICA (e.g. sphericity, omega complexity), the eigenvalues of each independent component, and the loadings of the factors for each image entered into the analysis.

## 1.3 Brain Electric Mechanisms and Modalities of Thinking

This section gives a review of the scientific literature associated with the relationship between modalities of thinking and brain (electric) mechanisms. Insights were included from other neuroscientific methods than EEG where appropriate.

### 1.3.1 Visual-Verbal Perception

Most research in neuroscience on modality-related information processing did not investigate the neural underpinnings of modality-related internal representations but the perception of information presented in different modalities. These studies used various methodologies including neuroanatomy, lesion studies, and neuroimaging in animals and humans, to successfully identify distinct[10] subsystems of the nervous system related to visual and auditory (speech / language) processing. [11]

The neuronal pathways associated with modality-related perception may not be identical to the neuronal pathways associated with modality-related mental representations, but they may substantially overlap. Consequently, they are shortly described.

***The Visual System***

Visual signals are transduced in the retina, and further propagated to the optic chiasm, the lateral geniculate nucleus (or superior colliculus), to then finally arrive at the striate cortex, also known as the primary visual cortex (Bruce, Green, & Georgeson, 2003). From the primary visual cortex, visual information processing continues across a hierarchy of levels (Felleman & Van Essen, 1991). A simplified conceptualization distinguishes two pathways: the dorsal and ventral visual pathway (Mishkin & Ungerleider, 1982). The dorsal pathway ascends from the primary visual cortex to a posterior parietal region. The ventral pathway ascends from the primary visual cortex to the inferotemporal cortex. The former (also referred to as “where stream”) has primarily been associated with processing of spatial information such as location, movement, spatial transformations, and spatial relations of objects. The latter (also referred to as “what stream”) has primarily been associated with the processing of

[10] It is worth mentioning that these subsystems are not completely independent but also include neurons which exhibit processing of another than the primary modality. Moreover, these networks comprise several inter-connections.

[11] Speech perception has often been investigated as a particular type of sensory input that is initially processed by the auditory system. However, verbal processing is not only related to speech perception but also to language perception in general. The perception of language is not dependent on the auditory modality but can also be triggered by visual input, i.e. in the context of reading.

Furthermore, verbal processing and internal verbalization may not only be associated with the perception of language but also with the internal production of language. Studies have shown that depending on whether an individual is requested to internally verbalize or internally imagine another person speak, different brain areas are activated which reportedly exhibit verbal perception and verbal production respectively (e.g. McGuire et al., 1996; Shergill et al., 2001).

object-visual information such as color, texture, pictorial detail, shape, and size (Vanni, Revonsuo, & Hari, 1997).[12]

### *The Auditory System*

Auditory signal transduction starts at the hair cells in the cochlea of the inner ear, and is then further propagated to the cochlear nucleus, the superior olivary complex (pons), the inferior colliculus (midbrain), the thalamus, and finally to a region in the temporal lobe referred to as the primary auditory cortex (Seldon, 1985). As for visual processing, a distinction between a dorsal and ventral stream of language processing has been proposed (Hickok & Poeppel, 2004, 2007; Scott & Wise, 2004). The dorsal stream ascends from the posterior temporal lobe of the left hemisphere through inferior parietal areas to the left inferior frontal gyrus (including premotor areas). The ventral stream ascends from the upper posterior part of the temporal lobe, to the anterior part of the temporal lobe where it connects to the ventral part of the inferior frontal gyrus. The former has primarily been associated with mapping sounds to motor programs and is thus important for verbal repetition and speech production (Grodzinsky & Santi, 2008; Ueno & Lambon Ralph, 2013; Ueno, Saito, Rogers, & Lambon Ralph, 2011). The latter has primarily been associated with the decoding of speech and extraction of meaning (Ueno & Lambon Ralph, 2013; Ueno et al., 2011).

Visual- and auditory speech perception were also associated with brain electric changes assessed via EEG, MEG, and intra-cortical recordings. They are reviewed in Manuscript 3. In sum, visual and auditory perception are associated with spectral power decreases in the range of the alpha frequency band in modality-related cortical regions (the occipital and temporal cortex, respectively) (see Niedermeyer, 1997; Pfurtscheller, 2003; Pfurtscheller & Da Silva, 1999 for reviews).

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[12] These associations, between the dorsal and ventral stream with spatial-visual and object-visual processing, respectively have also been challenged. For example, Goodale & Milner 1992 suggested that the functional distinction between the two streams may be more closely related to the output requirements of the visual input. They gathered evidence that shows that the identification of movement-related objects, such as tools, also activates areas of the dorsal and not only ventral visual pathway. Consequently, they suggested that the dorsal stream is associated with visually guided reaching and grasping, whereas the ventral stream is associated with object identification.

### 1.3.2 Visual-Verbal Internal Representation

***Imagery***

Visual and verbal mental representations can be induced via visual and verbal imagery tasks, respectively.

The brain regions associated with visual imagery reportedly overlap with those associated with visual perception. However, the degree of this overlap and its neural substrate have been a matter of debate. An early theory suggested that visual perception and visual imagery rely on a common neural substrate in the primary visual cortex (Kosslyn, 1980). However, this theory was challenged by subsequent neuroimaging and lesion studies. Several neuroimaging studies reported no activity in the primary visual cortex during visual imagery (Amedi, Malach, & Pascual-Leone, 2005; Daselaar, Porat, Huijbers, & Pennartz, 2010; Ishai, Ungerleider, & Haxby, 2000; Knauff, Kassubek, Mulack, & Greenlee, 2000) . Lesion studies described patients with intact visual mental imagery but impaired visual perception based on primary visual cortex deficiencies (see Bartolomeo, 2002 for a review). A comprehensive review suggests that rather than the primary visual cortex, intact extra-striate visual areas (parietal for spatial visual, temporal for object visual) may be decisive for visual imagery (Bartolomeo, 2002).

The brain regions associated with verbal imagery also reportedly overlap with those associated with speech perception and production (see Hubbard, 2010 for a review). When participants are required to imagine listening to someone else speak, speech perception-related areas are activated, whereas when required to generate speech, for example by silent articulation, speech production-related areas are activated (McGuire et al., 1996; Shergill et al., 2001).

With regard to visual- and auditory imagery, some reports suggest that visual-imagery decreases occipital EEG alpha activity (Kaufman, Schwartz, Salustri, & Williamson, 1990; Salenius, Kajola, Thompson, Kosslyn, & Hari, 1995; Slatter, 1960). However, I am not aware of studies that report similar effects for speech imagery on temporal alpha (e.g. Kreitman & Shaw, 1965; Slatter, 1960). The few early studies that investigated this topic tended to rely on global measures of EEG activity and did not use source-localization procedures which may be necessary to better distinguish occipito-parietal from occipito-temporal alpha effects.

***Thoughts***

Visual and verbal mental representations can also be investigated without relying on imagery tasks, for example, by post-hoc identification of thought modality or by other means of visual or non-visual thought induction.

Such approaches were applied by several EEG studies. For example, one study obtained self-report ratings on the degree of visual and verbal mental representations during the execution of several cognitive tasks. Correlation analyses associated verbal representations with greater left hemispheric, and visual representations with greater right-hemispheric activation (Ehrlichman & Wiener, 1980).

A second study identified time periods of visual as opposed to non-visual thought content during eyes closed resting by asking for self-reports of the thought they had just conceived after signal prompts (Lehmann et al., 2004). A third study triggered visual and non-visual thoughts by displaying concrete and abstract nouns (Koenig, Kochi, & Lehmann, 1998). Subsequent EEG microstate-based analyses of the latter two studies revealed similar topographical differences between thoughts rated as primarily visual vs. abstract, and thoughts induced by concrete vs. abstract nouns, respectively. Right posterior activity increased for visual mental representations and left anterior activity increased for non-visual mental representations (Lehmann, Pascual-Marqui, Strik, & Koenig, 2010).

### 1.3.3 Visual-Verbal Cognitive Style

Visual and verbal mental representations are applied in different degrees by different individuals depending on their visual-verbal cognitive style. Consequently, visual-verbal cognitive styles may affect tonic and / or phasic activity in modality-related brain regions during tasks and resting (see Manuscript 3 for a more detailed explanation).

Despite the popularity of the assessment of visual-verbal cognitive style, only few studies aimed to investigate its neural basis. Consequently, a recent review of the literature concluded that the neural underpinnings of visual-verbal cognitive style had remained largely elusive (Kraemer, Hamilton, Messing, DeSantis, & Thompson-Schill, 2014). The few studies that aimed to identify the neural basis of visual-verbal cognitive style are described as follows.

An early EEG study reported lower eyes-closed occipital alpha amplitudes for visualizers compared to verbalizers (N=60, Golla, Hutton, & Walter, 1943). This finding agrees with other reports that suggest that parieto-occipital alpha power decreases with increased demands on visual processing (Berger, 1933, see also Manuscript 3; Lehtonen & Lehtinen, 1972; Pollen & Trachtenberg, 1972; Ray & Cole, 1985). However, subsequent studies were not able to replicate this finding (see A. Richardson, 1969 for a review). A later study, reported higher dominant alpha frequency for vivid as opposed to non-vivid visualizers during an eyes open task (N=30, Gale, Morris, Lucas, & Richardson, 1972).

In recent years, a new series of studies attempted to investigate the interrelationships between visual-verbal cognitive style and brain activity. An EEG study identified visualizers and verbalizers in a group of 15 participants based on the Cognitive Style Analysis (Riding & Cheema, 1991). The EEG alpha activity of the two groups were compared during a verbal working memory task. The results suggested more left than right hemispheric suppression for verbalizers and more right than left hemispheric suppression for visualizers (Riding, Glass, Butler, & Pleydell-Pearce, 1997). A subsequent EEG study (Gevins & Smith, 2000) identified strong visualizers and verbalizers based on their relative performance on visual and verbal cognitive tests (N=16). The EEG alpha activity of the two groups were compared during a spatial working memory task. The results suggested greater left parietal activity (as indicated by hemispheric asymmetry) for verbalizers compared to visualizers.

An fMRI study (Motes, Malach, & Kozhevnikov, 2008) identified spatial and object visualizers based on questionnaires (Object Spatial Imagery Questionnaire by Blajenkova et al., 2006; Vividness of Visual Imagery Questionnaire by Marks, 1973) and spatial-ability tests (N=17). The blood oxygen level dependent (BOLD) activity was compared between the two groups during an object-visual task. The results suggested higher activity in parts of the object-visual stream for spatial compared to object visualizers (as indicated by higher bilateral activity in a lateral occipital complex). Since task performance did not differ between groups, the authors concluded that object visualizers needed fewer neural resources to perform equally well as spatial visualizers. A subsequent fMRI study (Hsu, Kraemer, Oliver, Schlichting, & Thompson-Schill, 2011) assessed visual-verbal cognitive style based on the Visualizer-Verbalizer Questionnaire (VVQ: modified by Kirby et al., 1988, N=12). Style was correlated with BOLD activity during a color knowledge retrieval task. The results indicated a positive association between visual cognitive style and brain activity in the left lingual gyrus. In this experiment, visual style was positively associated with task performance and the left lingual gyrus was associated with color perception. Presumably, visual cognitive style leads to increased activity in task-relevant visual areas, which in turn leads to superior task performance.

Another fMRI study (Kraemer et al., 2009) also assessed visual-verbal cognitive style based on the VVQ (N=18). Style was correlated with BOLD activity during visual and verbal tasks. The results indicated a positive association between visual and verbal cognitive styles with cortical areas associated with visual (fusiform gyrus) and verbal working memory (supramarginal gyrus), respectively. In a subsequent study, they showed that performance on a visual subtask of their previous experiment could be impaired by applying repeated transcranial magnetic stimulation (rTMS) to the area which had been associated with verbal working memory (N=21). The degree of impairment was positively correlated with verbal but not visual cognitive style (Kraemer et al., 2014).

The authors concluded that individuals process information in their preferred modality regardless of whether it is presented in their preferred form or not. For verbalizers, this would imply that they convert visual stimuli into verbal working memory representations, and that this strategy of conversion can be inhibited and performance impaired by rTMS to the required brain area (Kraemer et al. 2014). The authors refer to the process of transforming information to a preferred modality as conversion. They refer to the assumption that this process takes place in individuals when confronted with material of another modality, as the conversion hypothesis. They contrast this hypothesis with the matching hypothesis (also referred to as meshing hypothesis). The matching hypothesis suggests that individuals rely on information being presented in their preferred modality for optimal information acquisition (see Pashler et al., 2008 for a review).

### 1.3.4 Conclusion

The literature review on brain mechanisms of modalities of thinking suggests that a considerable amount of studies investigated the neural underpinnings of visual- and verbal- perception and imagery. Research on visual perception and verbal (speech) perception identified two distinct subsystems of the nervous system related to visual and verbal processing, respectively. Imagery studies suggested an overlap between the areas associated with perception and imagery. For visual imagery, this overlap may primarily concern extrastriate rather than primary visual areas (Bartolomeo, 2002). For verbal imagery, areas related to imagining others speak may differ from areas related to internally speaking oneself (McGuire et al., 1996; Shergill et al., 2001).

By contrast, only few studies have investigated the interrelationships between neural activity with visual-verbal cognitive style. Some suggested increased (Gevins & Smith, 2000; Golla et al., 1943; Hsu et al., 2011; Kraemer et al., 2009; Riding et al., 1997), others decreased (Motes et al., 2008) activity in cortical areas exhibiting processing in the favored[13] modality. Increased activity in style-associated neural networks was suggested to reflect the preference for processing information in the respective modality (as also proposed by the conversion hypothesis). Decreased activity in style-associated neural networks was interpreted as increased neural efficiency of the individuals that routinely apply the respective network.

These previous studies suffer from a number of limitations. Firstly, older studies failed to be replicated. Secondly, more recent studies have small sample sizes ($N \leq 22$) and heterogeneous sample compositions (males and females, sometimes lack of handedness specification). Thirdly, the latter relied on eyes open tasks which involved motor responses. Thus, they require afferential and efferential modality-related processing which may confound effects of the brain activity associated with visual and verbal mental representations and / or cognitive style. Fourthly, except one study (Motes et al., 2008), previous studies did not distinguish between spatial- and object-visual style. Since spatial- and object-visual processing are associated with brain activity in different neural pathways, this lack of distinction might also bias results. Fifthly, several studies included ability measures for cognitive style assessment (Gevins & Smith, 2000; Motes et al., 2008) or self-report measures which include items that ask for ability self-reports (Hsu et al., 2011, Kraemer et al., 2014; Kraemer et al., 2009; Motes et al., 2008). Consequently, the reported results may be reduced to effects of modality-related abilities rather than visual-verbal cognitive style.

Finally, the applied brain data acquisition and analysis methods are also affected by limitations. The fMRI studies suffer from the imaging method’s low temporal resolution and the assessment of a measure affected by blood metabolism rather than neural activity directly. The reported EEG studies reported very simple measures that were often based on a single frequency band (e.g. alpha amplitude, peak frequency,

[13] In this thesis, favored refers to frequency / habit not preference / enjoyment.

hemispheric asymmetry). Thus, they failed to take full advantage of the high temporal resolution of the EEG and the sophisticated source localization procedures available today.

This thesis presents EEG data from a comparably large, homogenous sample of 61 participants during tasks and resting. For each participant, the following person parameters were obtained: visual-verbal cognitive style, modality-related abilities, and self-reports on induced and spontaneous thinking modality. EEG data were analyzed using two sophisticated EEG analysis approaches: the EEG microstate analysis and the EEG functional independent component analysis (fICA). Statistical analyses identified effects of tasks on EEG measures and correlations of person parameters with EEG measures. Thus, it allowed the distinction between modality-specific processing associated with states vs. traits. The EEG Data Assessment is described in Section 1.4 of this thesis and in detail in Manuscript 2. The results retrieved from the EEG microstate analysis are reported in Manuscript 2; the results retrieved from the fICA are reported in Manuscript 3.

## 1.4 Data Assessments

In the context of this thesis, I conducted three data assessments. Data Assessments 1 and 2 served the construction and validation of a new visual-verbal cognitive style questionnaire. Data Assessment 3 served the investigation of the interrelationships between brain electric mechanisms and modalities of thinking. They are shortly described as follows. Detailed descriptions can be found in Manuscript 1 for Data Assessment 1 and 2 and in Manuscript 2 for Data Assessment 3.

Data Assessment 1 served the development of the Modality of Thinking Questionnaire (MOTQ). The MOTQ is a self-report questionnaire which assesses an individual's ability to acquire (learning style), their propensity to represent (cognitive style), and their ability to process information (ability) in a spatial-visual, object-visual, or verbal format. Its construction is based on the object-spatial-verbal cognitive style model[14] (Blazhenkova & Kozhevnikov, 2009). To develop the MOTQ, we created an item pool from previous questionnaires related to visual-verbal learning and cognitive

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[14] This thesis applies the terms spatial-object-verbal cognitive style and object-spatial-verbal cognitive style inter-changeably.

style and from self-constructed items. Visual items from previous questionnaires were refined to distinguish between spatial-visual and object-visual aspects. They were also adapted for each modality, that is from each visual item a corresponding verbal item was constructed and vice-versa. They were further adapted for each subscale, that is for each ability-related item, a cognitive style or learning style related item was constructed, where possible. Self-constructed items relied on the definitions of spatial-visual, object-visual, and verbal cognitive style (Blazhenkova & Kozhevnikov, 2009; Hegarty & Kozhevnikov, 1999), and descriptions of what modality-specific ability tests measure. From this item pool, the 45 items with highest content validity were extracted based on expert ratings. Then, they were evaluated in a convenience sample of 147 participants and reduced to 36 items based on their factor loadings, item-to-scale correlations, and content-related aspects[15].

Data Assessment 2 served the evaluation of the MOTQ developed in Study 1. We investigated the MOTQ's factorial structure, reliability, and validity, and its usefulness to cluster participants into modality-related types. We recruited 468 students aged 18 to 35. For each student, demographic variables were obtained (age, gender, degree program, university) and data from the MOTQ questionnaires at two time points. Self-reports on object-visual ability were obtained via the Vividness of Visual Imagery Questionnaire (Marks, 1973); and an additional cognitive style assessment was obtained based on the Object-Spatial Imagery and Verbal Questionnaire (Blazhenkova & Kozhevnikov, 2009).

Data Assessment 3 served the investigation of the interrelationships between modality-related states and traits with brain electric mechanisms. EEG and behavioral data were obtained from 70, right-handed, healthy, male participants aged 18 to 34, at three time points. At Time Point 1, individuals were screened for history of head trauma, brain disease, or current drug usage and did a MOTQ and VVIQ assessment. At Time Point 2, individuals completed the Edinburgh Handedness Test (Oldfield, 1971), the OSIVQ, modality-related cognitive tests, and the Object-Spatial-Visual Memory Test (OSVMT). Also their EEG was recorded during four different conditions:

[15] Content-related aspects refer here to content validity: the degree to which the collection of items is a representative selection of the construct aimed to be assessed (Amelang and Schmidt-Atzert, 2006). For example, we tried to avoid items that appeared too similar to instead cover various contexts.

resting, spatial visualization, object visualization, and verbalization. At Time Point 3, individuals completed the MOTQ and OSIVQ a second time.

The OSVMT is a self-constructed test that was not yet validated. Consequently, its results are not reported in any of the three manuscripts. However, preliminary results are reported in Unpublished Results. The OSVMT consists of ten images of living rooms. Each image is presented for 15 seconds. Then the participant is asked three multiple choice questions on spatial or object visual aspects of the image. In sum, there are 30 questions, 15 on spatial-visual, 15 on object-visual aspects. Spatial-visual aspects include spatial relationships between objects and spatial locations of objects. Object-visual aspects include surface texture, color, form, pictorial detail, and shape. Spatial- and object-visual questions are approximately equally distributed across images. I implemented the test in the software Presentation® (http://www.neurobs.com).

Data Assessment 1 and 2 formed the basis of Manuscript 3, Data Assessment 3 formed the basis of Manuscripts 2 and 3.

## 2. Manuscripts

This section contains the three manuscripts which were written in the context of this thesis.

### 2.1 Manuscript 1 (in preparation)

**The Modality of Thinking Questionnaire - Self-Report Measure of Object-Spatial-Verbal Cognitive Style**

#### 2.1.1 Abstract

Visual-verbal cognitive style refers to an individual's propensity to acquire, process, and represent information in a visual or verbal format. The present study reviews limitations of previous assessment approaches and introduces a new questionnaire, the Modality of Thinking Questionnaire (MOTQ) that does not suffer from these limitations. The MOTQ is based on the object-spatial-verbal cognitive style model and is compared to the Object-Spatial Imagery and Verbal Questionnaire (OSIVQ), the only other questionnaire based on this model. The MOTQ revealed a very satisfactory three-factor structure, internal and retest-reliability, and congruent and discriminant validity. Factor loadings, item-to-scale correlations, and structural equation modelling suggest its superior factorial structure over the OSIVQ. Cluster analysis results revealed that individuals can be categorized into seven reliable and valid types based on their MOTQ scores. MOTQ type prevalence differed between genders and students of various degree programs. Future studies must reveal their association with particular neurophysiological pathways. Visual-verbal cognitive style refers to an individual's propensity to acquire, process, and represent information in a visual or verbal format. The present study reviews limitations of previous assessment approaches and introduces a new questionnaire, the Modality of Thinking Questionnaire (MOTQ) that does not suffer from these limitations. The MOTQ is based on the object-spatial-verbal cognitive style model and is compared to the Object-Spatial Imagery and Verbal Questionnaire (OSIVQ), the only other questionnaire based on this model. The MOTQ revealed a very satisfactory three-factor structure, internal and retest-reliability, and congruent and discriminant validity. Factor loadings, item-to-scale correlations, and structural equation modelling suggest its superior factorial structure over the OSIVQ. Cluster analysis results revealed that individuals can be categorized into seven reliable and valid types based on their MOTQ scores. MOTQ

type prevalence differed between genders, and students of various degree programs. Future studies must reveal their association with particular neurophysiological pathways.

### 2.1.2 Introduction

***Visual-Verbal Cognitive Style***

Cognitive style refers to a number of psychological dimensions that represent consistencies in an individual's manner of acquiring, processing, and representing information (Ausburn & Ausburn, 1978; Kozhevnikov, 2007; Messick, 1976; Witkin, 1967). Since the early 1950s, a tremendous number of cognitive styles in both the theoretical and applied literature have been proposed which are thought to identify "individual differences in cognition that are stable, value free, and related to personality and social relationships" (Kozhevnikov, 2007, p. 464). The topic of this paper is the visual-verbal cognitive style dimension (Blazhenkova & Kozhevnikov, 2009; Paivio, 1971; A. Richardson, 1977). Visual-verbal cognitive style refers to an individual's propensity to acquire, process, and represent information in a visual or verbal format, in images or in words. Limitations of previous assessment approaches of visual-verbal cognitive style are reviewed and a new approach is proposed that allows the assessment of individuals on three independent scales and their classification into types of different processing styles.

***The Object-Spatial-Verbal Cognitive Style Model***

The traditional model of visual-verbal cognitive style proposes that individuals can be positioned on a continuum between visualizer and verbalizer, that is, individuals who primarily acquire, process, and represent information in images are contrasted with individuals who primarily acquire, process, and represent information in words (e.g. Blazhenkova & Kozhevnikov, 2009; Paivio, 1971; A. Richardson, 1977). This traditional model has been challenged by a new object-spatial-verbal cognitive style model (Blazhenkova & Kozhevnikov, 2009) which differs from the traditional model in two respects. Firstly, visualization-verbalization is no longer regarded as one bipolar dimension ranging from visualization to verbalization but rather as two independent unipolar dimensions, suggesting that a strong visualizer does not need to be a weak verbalizer, or vice versa. Secondly, a subdivision of the visualization dimension into the two separate independent dimensions, *spatial visualization* and *object visualization* is proposed. This new model was supported by findings from individual differences (Blajenkova, Kozhevnikov, & Motes, 2006; Kozhevnikov, Hegarty, & Mayer, 2002; Kozhevnikov, Kosslyn, & Shephard, 2005), neuropsychology (e.g. Britz, Van De Ville, & Michel, 2010; Cabeza & Nyberg, 2000; Farah, Hammond, Levine, & Calvanio, 1988; Gazzaniga, 2004; Kosslyn, Ganis, & Thompson, 2001; Lehmann, Pascual-Marqui, Strik, & Koenig, 2010; Mantini, Perrucci, Del Gratta, Romani, & Corbetta, 2007; Mellet et al., 2002; Thierry & Price, 2006), and structural equation modelling (Blazhenkova & Kozhevnikov, 2009).

***The Object-Spatial Imagery and Verbal Questionnaire (OSIVQ)***

To assess visual-verbal cognitive style based on the new object-spatial-verbal cognitive style model, the Object-Spatial Imagery and Verbal Questionnaire (OSIVQ: Blazhenkova & Kozhevnikov, 2009) was developed. The OSIVQ comprises three scales (15 items each) to assess the three dimensions object-visualization (imagery), spatial-visualization (imagery), and verbalization. The OSIVQ has been evaluated with regard to internal reliability, construct validity, criterion validity, and ecological validity (OSIVQ: Blazhenkova & Kozhevnikov, 2009), and it has been applied in several studies (e.g. Aggarwal & Woolley; Johansson, Holsanova, & Holmqvist, 2011; Madzharov & Block, 2010).

However, the OSIVQ suffers from a number of critical problems. Firstly, a third of its items (14 of 45) force the respondent to choose between two of the three dimensions (e.g. OSIVQ 28 from Blazhenkova & Kozhevnikov, 2009). These bipolar items undermine the questionnaire’s ability to assess its’ three dimensions independently. The participant is forced to choose one dimension over the other or neither dimension without an option to express a strong or low application of both dimensions.

Secondly, almost half of its items (21 of 45), unevenly distributed across scales, ask the respondent for the self-report of an ability (e.g. OSIVQ 16 from Blazhenkova & Kozhevnikov, 2009). These items undermine the questionnaire’s ability to assess visual-verbal cognitive style thoroughly and well-balanced within and across scales. According to their definition, cognitive style dimensions are related to but their assessment should not be reduced to or biased towards ability (Antonietti & Giorgetti, 1992; Ausburn & Ausburn, 1978; Katz, 1983; Mayer & Massa, 2003; Messick, 1976). Moreover, the choice of such item types might lead to over-estimations in criterion validity when correlations with cognitive ability tests are used (as in Blazhenkova & Kozhevnikov, 2009). Strong correlations with ability tests of scales where self-reported ability items are over-represented might simply reflect associations between self-reports and test performances rather than an association between style and ability.

Thirdly, four of its items, again unevenly distributed across scales, request the self-report of a career path preference or ability (e.g. OSIVQ 3 from Blazhenkova & Kozhevnikov, 2009). These items might again undermine the questionnaire's ability to assess visual-verbal cognitive style thoroughly and well-balanced within and across scales. Cognitive style dimensions are reported to be related to career path preferences but do not directly assess them. Moreover, the choice of such item types might lead to over-estimations in ecological validity when correlations with career paths are used (as in Blazhenkova & Kozhevnikov, 2009).

***The Modality of Thinking Questionnaire (MOTQ)***

To remedy these problems, we developed a new questionnaire to assess an individual's object-spatial-verbal cognitive style, the Modality of Thinking Questionnaire (MOTQ). The MOTQ was constructed based on an item pool comprising self-constructed items and items from available previous questionnaires related to visual-verbal cognitive style (e.g. the VVQ by A. Richardson, 1977, the SOP by Childers, Houston, & Heckler, 1985, complete list available at author request). From this item pool, the 45 items with highest content validity were extracted based on expert ratings. These 45 items were then evaluated in a convenience sample of 147 participants and reduced to 36 items based on their factor loadings, item-to-scale correlations, and content-related aspects. The 36 remaining items were re-evaluated by two independent raters, in the process of which eight items were simplified or reformulated for the sake of clarity.

Compared to the OSIVQ, the MOTQ has three fundamental advantages. Firstly, it comprises only unipolar items that do not force a respondent to choose between two dimensions (e.g. between spatial-visual and verbal) and thus avoids biasing the scales' factorial structure towards interdependency. Secondly, it comprises an equal number of items across and within scales of three indicators of visual-verbal cognitive style: participants' efficiency at acquiring ('learning'), their habit to represent ('habit'), and their ability to process ('ability') information in a given modality. Thirdly, it uses no items that ask for the self-reported ability in or the preference for a particular career path.

***Problems of the Previous Attempts to Categorize Participants into Types***

Beyond simply obtaining their scores on one or a number of dimensions, the assessment of visual-verbal cognitive style has also been used for categorizing individuals into groups, e.g. visualizers and verbalizers, or object-visualizers and spatial-visualizers. To group individuals, previous approaches used a cut-off criterion applied to one single dimension of visual-verbal cognitive style at a time e.g. (Blazhenkova & Kozhevnikov, 2009; Kozhevnikov et al., 2005; Mayer & Massa, 2003; Paivio, 1971; Peterson, Deary, & Austin, 2005; A. Richardson, 1977). Instead, we propose that all three dimensions of the new object-spatial-verbal cognitive style model should be used simultaneously. This approach has the advantage that it accounts for the three-factor structure of the construct and allows the categorization of individuals into groups based on participants' individual profiles rather than solely their absolute scores compared to others on one dimension; a measure which is likely to be subject to response biases (Choi & Pak, 2005).

***The Present Work***

The present study (1) thoroughly evaluated and compared the MOTQ to the OSIVQ with regard to factorial structure, reliability, and validity and (2) used the scales of the MOTQ to compute a cluster analysis which shows that participants can meaningfully be clustered into groups when all three dimensions of the object-spatial-verbal cognitive style model are considered simultaneously. These groups were then evaluated with regard to reliability and validity.

### 2.1.3 Method

***Participants***

From the University of Zurich and the Swiss Federal Institute of Technology of Zurich, 468 students aged 18 to 35 (281 female; age $M$ = 23.6, $SD$ = 3.2) were recruited through forum posts, student mailing lists, and flyers in university buildings to take part in the present study. Demographic variables (age, gender, degree program, University) and data for three questionnaires were obtained (computerized versions) at two time points.

*Questionnaires*

**Modality of Thinking Questionnaire (MOTQ).** The MOTQ is a self-rating questionnaire which consists of 36 items, 12 items each to assess the three scales: spatial-visualization, object-visualization, and verbalization. Each scale is comprised of three subscales to assess a person's efficiency to acquire new information for learning (e.g.: "Creating schematic images of what I have learned is of great help to me while studying."), their habit to represent information in the respective modality (e.g.: "When sitting in a train and allowing my thoughts to wander, my thinking often takes place in a verbal form, i.e. I speak to myself internally."), and their ability to process information in the respective modality (e.g.: "I can easily cope with tasks that require the representation of spatial relationships between objects and their spatial transformation."). In each item, participants are asked to identify the degree of agreement with the modality specific statement on a 5-point Likert-scale ranging from 1 (*complete disagreement*) to 5 (*absolute agreement*). MOTQ scores for the scales and subscales were obtained by computing the mean of the respective items.

**Object-Spatial Imagery and Verbal Questionnaire (OSIVQ).** The German version of the OSIVQ (Blazhenkova & Kozhevnikov, 2009) purchased via MM Virtual Design (mmvirtualdesign.com) was used to have an alternative measurement of a person's visual-verbal cognitive style. The OSIVQ is a self-rating questionnaire which consists of 45 items, 15 items each to assess the three scales: spatial imagery, object imagery, and verbalization. In each item, participants are asked to identify the degree of agreement with a modality specific statement on a 5-point Likert-scale ranging from 1 (*complete disagreement*) to 5 (*absolute agreement*). The four negatively worded items were reverse-coded for the analysis. OSIVQ scores were obtained by computing the mean of all items for each OSIVQ scale.

**Vividness of Visual Imagery Questionnaire (VVIQ).** A German translation of the VVIQ was used to assess a person's object-visual ability (Marks, 1973). The VVIQ is a self-rating questionnaire which consists of 16 items. Each item describes a mental image or a modification of a mental image. The participant is asked to mentally produce this image and rate its vividness on a Likert-scale (e.g. "Visualize the rising sun. Consider carefully the picture that comes before your mind's eye. The sun is rising above the horizon into a hazy sky.") ranging from 1 (*no image at all, you only "know" that you are thinking of an object*) to 5 (*perfectly clear and as vivid as normal vision*) (reversed rating scale as recommended by McKelvie, 1995). The internal reliability of the VVIQ is Cronbach's alpha ≈ .88 (McKelvie, 1995). The participants were asked to visualize the images with their eyes closed. VVIQ scores were obtained by averaging the ratings of all 16 items.

***Procedure***

At time point 1, the participants received the MOTQ and, after its completion, the Vividness of Visual Imagery Questionnaire (VVIQ: Marks, 1973). Eight weeks later, at time point 2, the participants received the MOTQ a second time and, after its completion, the OSIVQ.

At time point 1, the MOTQ was completed by 468 students (281 female; age *M* = 23.6, *SD* = 3.2); the VVIQ was completed by 291 of these students (240 female; age *M* = 23.4, *SD* = 3.3). At time point 2, the MOTQ was completed by 197 students (170 female; age *M* = 23.2, *SD* = 3.3), i.e. 42% of the original sample and the OSIVQ was completed by 161 of these students (139 female; age *M* = 23.3, *SD* = 3.4). The participants had to answer each item before the questionnaire could be submitted. Therefore, when a questionnaire was completed by a given participant, there were no unanswered items within this questionnaire.

There was no time limit for the completion of any of the above questionnaires. Not all questionnaires were completed by all participants because they were free to quit their participation at any point of the study. We used all available data. If participants wished to receive their personal feedback scores, they could check a respective box at either time point, whereupon they received their personal feedback scores after the completion of the second data assessment and a thank you note for their participation.

Psychology students additionally received partial course credit after their participation.

### 2.1.4 Results

***Descriptive Data on the Questionnaires***

**MOTQ.** The distributions of the three MOTQ scales (Table 1 top) were very similar (see also Figure 1 left). All MOTQ scales were normally distributed with however, slight deviations from the normality line for extreme values smaller than 1.75 and greater than 4.5, where the scales were negatively skewed (as revealed by qq-plot inspections).

*Table 1*

Scale Descriptives of the MOTQ (N = 468) and OSIVQ (N = 161)

| Questionnaire | Scale | *M* | *SD* | Skew | Kurtosis |
|---|---|---|---|---|---|
| MOTQ | spatial | 3.48 | 0.68 | -0.30 | -0.36 |
| | object | 3.45 | 0.68 | -0.42 | -0.07 |
| | verbal | 3.48 | 0.63 | -0.31 | -0.28 |
| | | | | | |
| OSIVQ | spatial | 2.90 | 0.73 | 0.00 | -0.35 |
| | object | 3.26 | 0.75 | -0.55 | -0.25 |
| | verbal | 3.18 | 0.64 | -0.40 | -0.03 |

**OSIVQ.** The distributions of the three OSIVQ scales (Table 1 bottom) varied more strongly than those of the MOTQ (see Figure 1 right). Only the OSIVQ spatial scale was normally distributed. The OSIVQ object and OSIVQ verbal scales showed deviations from the normality line, especially for extreme values smaller than .2 and greater than 4.5 where the scales were negatively skewed.

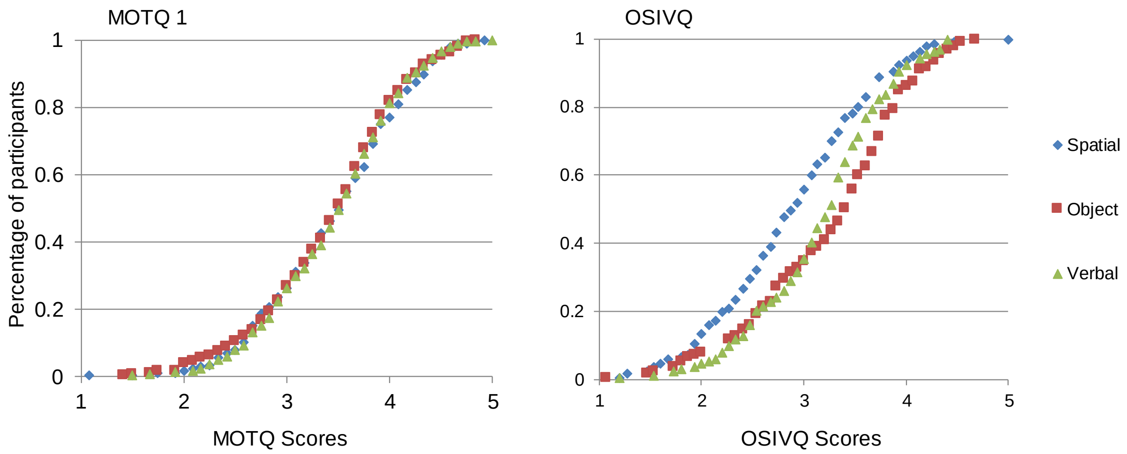


*Figure 1.* The correspondence of the MOTQ 1 (N = 468) and the OSIVQ (N = 161) scores to participants' percentiles on the spatial, object, and verbal scales.

### *Factorial Structure*

**Exploratory principal component analysis.**

***MOTQ.*** The first, exploratory principal component analysis of all MOTQ items revealed 8 factors with eigenvalues above 1. Only three of these factors, however, had eigenvalues markedly higher (7.18, 4.45, 2.90) than the others (ranging from 1.72 to 1.00). The first three factors explained 40.36% of the variance. The second principal component analysis was performed with three fixed factors and varimax rotation. Explained variances for the three factors after rotation were 15.18%, 13.48%, and

11.71%. Table 2 (left) shows the loadings of the 36 MOTQ items on the three factors ordered by scale and subscale (item texts in English and original German questionnaire in presentation order are available at author request). All of the items designed to assess spatial-visualization loaded highest on Factor 1; all items designed to assess object-visualization loaded highest on Factor 2; and all items designed to assess verbalization loaded highest on Factor 3. With the exception of two items (motq25, motq29), all items loaded at least .4 on their own factor (range = .32-.77). No item had positive or negative loadings above .4 on another factor than the one it was designed to assess.

***OSIVQ.*** The first, exploratory principal component analysis of all OSIVQ items revealed 10 factors with eigenvalues above 1. Only three of these factors, however, had eigenvalues markedly higher (8.90, 7.36, 3.86) than the others (ranging from 1.95 to 1.06). The first three factors explained 44.70% of the variance. The second principal component analysis was performed with three fixed factors and varimax rotation. Explained variances for the three factors after rotation were 19.65%, 13.00%, and 12.07%. Table 2 (right) shows the loadings of the 45 OSIVQ items on the three factors ordered by scale (for item texts see Blazhenkova & Kozhevnikov, 2009).

Of the 15 items designed to assess spatial imagery, only 9 items loaded highest on the respective Factor 2. The remaining 6 items loaded highest on Factor 1 (negative loadings). Of the 15 items designed to assess object imagery, 14 items loaded highest on the respective Factor 1. One item (osivq21) had an equally high loading on Factor 1 and Factor 2. Of the 15 items designed to assess verbalization, only 10 items loaded highest on the respective Factor 3. Two items (osivq38, 40) loaded highest on Factor1 (again negative loadings), three items loaded highest on Factor 2 (osivq37, 37, 39). In contrast to the MOTQ above, only 30 of the 45 items loaded at least .4 on their own factor (range=.10-.85). Moreover, 8 items had negative loadings above .4 on another factor than the one they were designed to assess.

*Table 2*

Principal Component Loadings after Varimax Rotation of the 36 MOTQ Items and the 45 OSIVQ items.

| Questionnaire | | | | | MOTQ |
|---|---|---|---|---|---|
| Main Scale | Sub Scale | Factor 1 | 2 | 3 | Item Index |
| Spatial | Learning | **.60** | .15 | -.19 | motq1 |
| | | **.59** | -.16 | -.03 | motq2 |
| | | **.66** | .31 | -.23 | motq3 |
| | | **.52** | -.06 | -.08 | motq4 |
| | Habit | **.51** | .29 | -.08 | motq5 |
| | | **.52** | .37 | .05 | motq6 |
| | | **.72** | -.14 | -.10 | motq7 |
| | | **.69** | .11 | -.11 | motq8 |
| | Ability | **.56** | .30 | .06 | motq9 |
| | | **.55** | -.10 | -.04 | motq10 |
| | | **.67** | .00 | -.07 | motq11 |
| | | **.75** | .12 | -.05 | motq12 |
| Object | Learning | .40 | **.59** | -.23 | motq13 |
| | | .36 | **.50** | -.18 | motq14 |
| | | .37 | **.41** | -.22 | motq15 |
| | | .28 | **.67** | -.14 | motq16 |
| | Habit | -.08 | **.56** | .08 | motq17 |
| | | .00 | **.62** | .07 | motq18 |
| | | .00 | **.59** | .03 | motq19 |
| | | .11 | **.77** | -.07 | motq20 |
| | Ability | -.08 | **.56** | -.01 | motq21 |
| | | .24 | **.45** | .13 | motq22 |
| | | .06 | **.63** | .11 | motq23 |
| | | -.19 | **.63** | .09 | motq24 |
| Verbal | Learning | -.28 | .02 | .32 | motq25 |
| | | -.13 | -.09 | **.50** | motq26 |
| | | -.06 | -.08 | **.44** | motq27 |
| | | -.32 | .00 | **.56** | motq28 |
| | Habit | -.03 | -.12 | .36 | motq29 |
| | | .00 | .18 | **.56** | motq30 |
| | | .08 | .21 | **.50** | motq31 |
| | | -.24 | -.15 | **.62** | motq32 |
| | Ability | -.07 | .02 | **.71** | motq33 |
| | | .07 | .01 | **.69** | motq34 |
| | | -.07 | .20 | **.62** | motq35 |
| | | -.07 | .03 | **.76** | motq36 |

| | | | | OSIVQ |
|---|---|---|---|---|
| Main Scale | Factor 1 | 2 | 3 | Item Index |
| Spatial | -.08 | **.79** | -.08 | osivq1 |
| | ***-.54*** | .35 | .05 | osivq2 |
| | -.13 | **.42** | -.21 | osivq3 |
| | ***-.52*** | .33 | .17 | osivq4 |
| | ***-.71*** | .29 | -.03 | osivq5 |
| | .02 | **.79** | -.06 | osivq6 |
| | ***-.62*** | .12 | -.02 | osivq7 |
| | .33 | **.59** | -.08 | osivq8 |
| | .04 | **.68** | -.10 | osivq9 |
| | -.13 | **.80** | -.20 | osivq10 |
| | -.12 | **.74** | .01 | osivq11 |
| | ***-.54*** | .18 | .02 | osivq12 |
| | ***-.76*** | .35 | -.04 | osivq13 |
| | .04 | **.71** | -.03 | osivq14 |
| | .18 | **.66** | -.24 | osivq15 |
| Object | **.76** | -.04 | .08 | osivq16 |
| | **.81** | .00 | .02 | osivq17 |
| | .34 | .12 | .08 | osivq18 |
| | **.58** | .34 | -.03 | osivq19 |
| | **.74** | .19 | .11 | osivq20 |
| | .33 | -.33 | .26 | osivq21 |
| | **.62** | .12 | -.05 | osivq22 |
| | **.73** | .08 | .00 | osivq23 |
| | **.67** | .09 | .04 | osivq24 |
| | .27 | .09 | .15 | osivq25 |
| | **.64** | -.01 | .12 | osivq26 |
| | **.69** | .10 | .12 | osivq27 |
| | **.58** | .12 | -.14 | osivq28 |
| | **.60** | .02 | .15 | osivq29 |
| | **.60** | -.05 | -.12 | osivq30 |
| Verbal | -.05 | -.07 | **.72** | osivq31 |
| | .04 | -.06 | **.56** | osivq32 |
| | .06 | -.11 | **.69** | osivq33 |
| | .20 | -.25 | **.74** | osivq34 |
| | .00 | -.14 | **.85** | osivq35 |
| | .02 | -.37 | .16 | osivq36 |
| | -.10 | -.39 | .32 | osivq37 |
| | ***-.50*** | -.04 | .10 | osivq38 |
| | -.24 | -.38 | .12 | osivq39 |
| | ***-.45*** | -.26 | .37 | osivq40 |
| | -.07 | -.19 | **.81** | osivq41 |
| | -.09 | -.07 | .36 | osivq42 |
| | .12 | -.05 | **.65** | osivq43 |
| | .06 | -.03 | **.78** | osivq44 |
| | .03 | -.15 | **.59** | osivq45 |

*Note.* Positive factor loadings >.40 are underlined and blue. Negative factor loadings <-.40 are italic and red.

**Confirmatory factor analysis.**

***MOTQ.*** We compared five models using structural equation modelling in IBM SPSS Amos (Version 22.0): a one-factorial bipolar model (visual-verbal factor: A. Richardson, 1977), a two-factorial unipolar model (visual, verbal factor: altered from A. Richardson, 1977), a three-factor unipolar model (object-visual, spatial-visual, verbal factor: Blazhenkova & Kozhevnikov, 2009), a three-x-three-factor unipolar model (primary factors: object-visual, spatial-visual, verbal factor, secondary factors: learning, habit, ability), and a multi-trait multi-method model (primary factors left: object-visual, spatial-visual, verbal factor; primary factors right: ability, habit, learning).

For each model, model-fit comparisons revealed that the three-factor models (Model 3-5: $\chi 2 \leq 2326$, df $\leq 591$, CFI $\geq .70$, RMSEA $\leq .08$) fit the data better than the one- and two-factor models (Models 1 and 2: $\chi 2 = 3947, 3067$; df = 594, 593; CFI = .43, .58; RMSEA = .11, .10). The best model-fit was observed for Model 5 ($\chi 2 = 1474$, df = 552, CFI = .84, RMSEA = .06). A visualization and standardized estimates of Model 5 and differential goodness-of-fit indices for nested models can be found in Supplementary Material Appendices A and B).

***OSIVQ.*** For the OSIVQ, we compared three models. The procedure was identical to the one explained for the confirmatory factor analysis of the MOTQ except that models 4 and 5 could not be tested due to the lack of a respective sub-structure in the OSIVQ. Model-fit comparisons again revealed a better fit of the three-factor model ($\chi 2 = 2407$, df = 942, CFI = .60, RMSEA = .10) compared to the two- and one-factor models ($\chi 2 = 2691, 3333$; df = 944, 945; CFI = .52, .34; RMSEA = .11, .13). Differential goodness-of-fit indices for nested models can be found in Supplementary Material Appendix B.

***Reliability: Internal Consistency and Re-Test Reliability***

**MOTQ.** Cronbach’s alpha was .86 for the spatial, .84 for the object, and .81 for the verbal scale. The scores of the sub-scales ranged from .57 through .81. Corrected item-to-scale correlations were greater than .3 for all 36 MOTQ items (range = .31-.71). Re-test reliabilities (8-week interval, N = 197) were r = .85, r = .87, and r = .86 for the spatial, object, and verbal scale, respectively. The correlation coefficients of the subscales ranged from .70 through .86. The correlation coefficients for all subscales can be found in Supplementary Material Appendix C.

**OSIVQ.** Cronbach's alpha was .86 for the spatial, .88 for the object, and .84 for the verbal scale. Corrected item-to-scale correlations were greater than .3 for 40 of the 45 OSIVQ items (range = .31-.71). There were 5 items with item-to-scale correlations below .3, two items of the object-visual scale (osivq21: .29 and osivq25: .26) and three items of the verbal scale (osivq36: .25, osivq38: .11, osivq39: .23). Due to the lack of a second measurement of the OSIVQ, re-test reliabilities could not be computed.

### *External Validity*

**VVIQ.**

***MOTQ.*** Correlations of the scales and subscales of the MOTQ 1 and MOTQ 2 with the VVIQ were high ($r = .67, .68$) with the object scale, low ($r = .28, .23$) with the spatial scale and not significant ($r = .10, .04$) with the verbal scale. Of the MOTQ subscales, the object-visual ability subscale correlated highest with the VVIQ ($r = .62, .70$ for MOTQ 1 and MOTQ 2 respectively, see also Supplementary Material Appendix D). We note that the correlations between the VVIQ and the MOTQ were overall higher for MOTQ 1 because MOTQ 1 was presented together with the VVIQ at the first assessment time point.

***OSIVQ***. Correlations of the OSIVQ scales with the VVIQ were high for the object scale ($r = .71$, $p<.001$, $N = 141$) and not significant for the spatial ($r = -.12$, $p = .165$, $N = 141$) and verbal ($r = -.12$, $p =.162$, $N = 141$) scales.

**Gender differences.** The OSIVQ and the MOTQ at both times of measurement showed the same pattern of gender differences. Men showed higher spatial but lower object scores compared to women; there was no significant difference between genders in verbal scores. The results of the respective MANOVAs are shown in Table 3 (top). Figure 2 illustrates the mean scores and distributions of the three scales by gender for the MOTQ 1, the MOTQ 2, and the OSIVQ. The results of the univariate ANOVAs can be found in Supplementary Material Appendix E.

*Table 3*

Multivariate Effects of the independent variables (IV) Gender and Degree Program on the dependent variables (dv) the MOTQ 1, MOTQ 2, and OSIVQ Scales.

| Independent Variable | Dependent Variable | *df* | *df error* | *F* | *p* | Wilks' Λ | partial η2 |
|---|---|---|---|---|---|---|---|
| Gender | MOTQ 1 | 3 | 464 | 40.072 | <.001 | 0.794 | 0.21 |
| | MOTQ 2 | 3 | 193 | 10.367 | <.001 | 0.861 | 0.14 |
| | OSIVQ | 3 | 157 | 10.532 | <.001 | 0.832 | 0.17 |
| Degree Program | MOTQ 1 | 6 | 884 | 23.116 | <.001 | 0.747 | 0.14 |
| | MOTQ 2 | 6 | 376 | 7.074 | <.001 | 0.807 | 0.10 |
| | OSIVQ | 6 | 306 | 4.236 | <.001 | 0.853 | 0.08 |

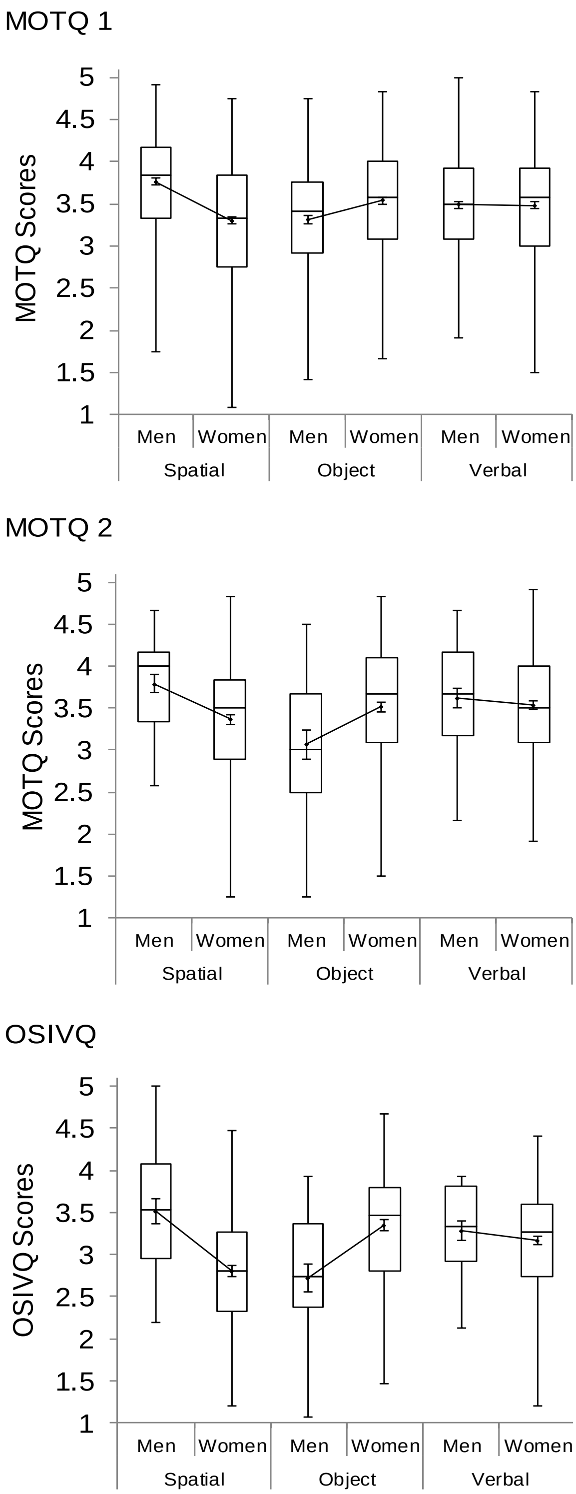


*Figure 2.* Box-Plots illustrating the effect of gender on the three scales spatial, object, and verbal for the MOTQ 1 (187 men, 281 women), the MOTQ 2 (27 men, 170 women), and the OSIVQ (22 men, 139 women). Boxes range from the first to the third quartile, the line represents the median. Diamonds represent the mean and the error bars standard errors of means.

**Degree program.** The MOTQ at both times of measurement showed the same pattern of degree program differences. Students of the natural sciences (high demands in formal and natural sciences) showed highest spatial but lowest verbal scores, whereas students of the humanities (high demands in language) showed lowest spatial and highest verbal scores. Students of the social sciences (heterogeneous demands) showed the highest object scores and were in-between the other two groups with regard to spatial and verbal scores. Similarly, for the OSIVQ, spatial scores were highest for the natural science students and verbal scores were highest for the humanity students. However, there were no significant differences between degree programs in OSIVQ object scores ($p<.05$ corrected for multiple testing). The results of the respective MANOVAs are shown in Table 3 (bottom). Figure 3 illustrates the mean scores and distributions of the three scales by degree program for the MOTQ 1, the MOTQ 2, and the OSIVQ. The results of the Univariate ANOVAs and follow up Games Howell t-tests can be found in Supplementary Material Appendix F.

**MOTQ and OSIVQ.** The correlations between the MOTQ 1 and 2 with the corresponding OSIVQ scales were high, $r > .70$, $p < .001$ for all three visual-verbal cognitive style dimensions. Of the MOTQ subscales, correlation coefficients were largest for the ability subscale (in five of six cases). The correlations between the OSIVQ and the MOTQ were overall higher for MOTQ 2 because the OSIVQ was presented together with the MOTQ 2 at the second assessment time point. Correlations between the MOTQ and the non-corresponding OSIVQ scales were low for all of the 12 cases (range: -.42 to .15), negative for 8 of the 12 cases and not significant ($p > .05$) for 5 of the 12 cases. All correlation coefficients can be found in Supplementary Material Appendices G and H.

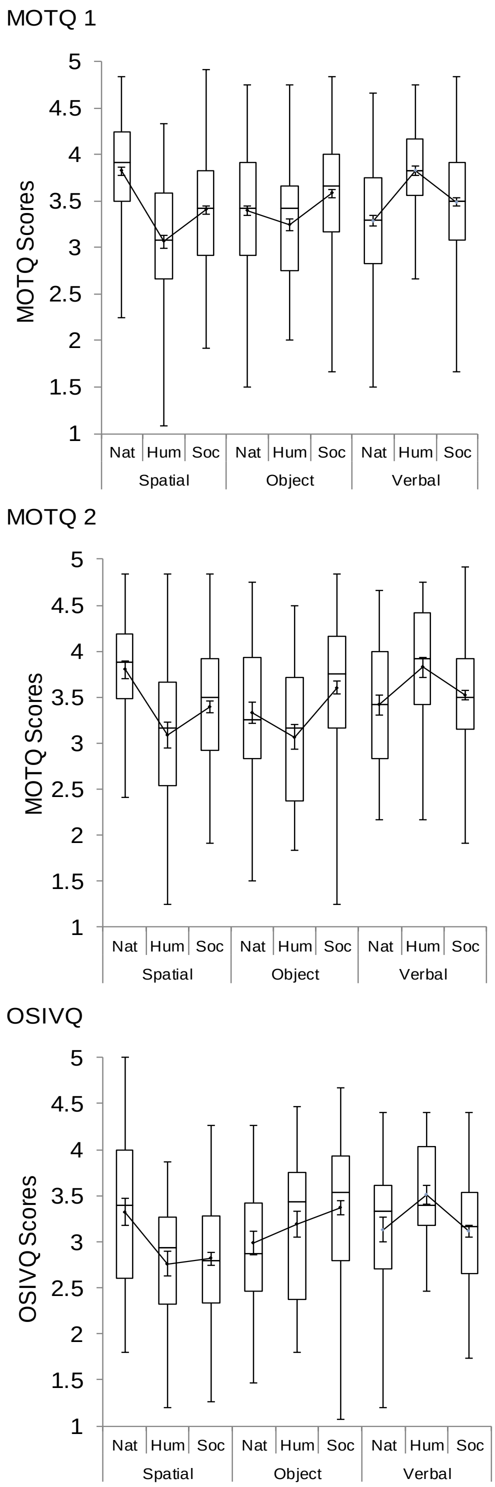


*Figure 3.* Box-Plots illustrating the effect of degree program on the three scales spatial, object, and verbal for the MOTQ 1 (n: 154 Nat: Natural Sciences, 86 Hum: Humanities, 207 Soc: Social Sciences), the MOTQ 2 (n: 42 Nat, 33 Hum, 118 Soc), and the OSIVQ (n: 30 Nat, 30 Hum, 98 Soc). Boxes range from the first to the third quartile, the line represents the median. Diamonds represent the mean and the error bars standard errors of means.

### *Cluster Analysis: Classification of Participants into MOTQ Types*

**Cluster description.** The primary interest of the analysis was to reveal personal style differences by investigating participants' profiles rather than their absolute scores or absolute differences between scores. Participants' individual profiles are comprised of their relative differences between scales. These relative differences were investigated by applying a z-transformation procedure to the raw data since without transformation the inter-individual variance obfuscated the smaller intra-individual variance. However, to avoid artificially blowing up the profiles of those individuals who show very similar scores on all three MOTQ scales, the first cluster was built to comprise all participants with very similar scores on all scales (cut off $SD < .20$ across the three MOTQ scales). In the second step, for the remaining participants, a two-step cluster analysis was computed based on their z-transformed MOTQ scores of the three scales (distance measure: Euclidian, Initial Distance Change Threshold = 0, Maximum Branches (per leaf node) = 8, Maximum Tree Depth = 3, Maximum Number of Nodes Possible = 585) in SPSS (version 22). The Bayesian Information Criterion (BIC) revealed an optimal number of six additional clusters with a good cluster quality (Silhouette coefficient=.6). For the 7 clusters, the mean values of the three z-transformed scores, and their distribution (median, 1st and 3rd quartile) compared to the whole sample are illustrated in Figure 4.

The participants of the first three clusters showed markedly higher scores on one compared to the other two scales. These MOTQ types were therefore labelled according to the scale where participants scored highest, i.e. spatial-visualizers, object-visualizers, and verbalizers. The participants of the second three clusters showed markedly lower scores on one scale compared to the other two scales. These MOTQ types were labelled according to the two scales where participants' scored comparably higher, i.e. spatial-object-visualizers, verbal-object-visualizers and verbal- spatial-visualizers. The participants of the seventh cluster showed very small differences between their spatial, object and verbal scores. They were therefore labelled multi-modalizers.

Inspecting cluster sizes reveals that most participants (20%) of our sample were classified as spatial-object-visualizers, thus scored high on both the spatial and object, but low on the verbal scale (20%). Whereas only half as many participants (11% and 9% respectively) reported high spatial but low object scores (spatial-visualizers) or the opposite, high object and low spatial scores (object-visualizers). In sum, only 38% of participants showed a clear preference of one modality over the other two.

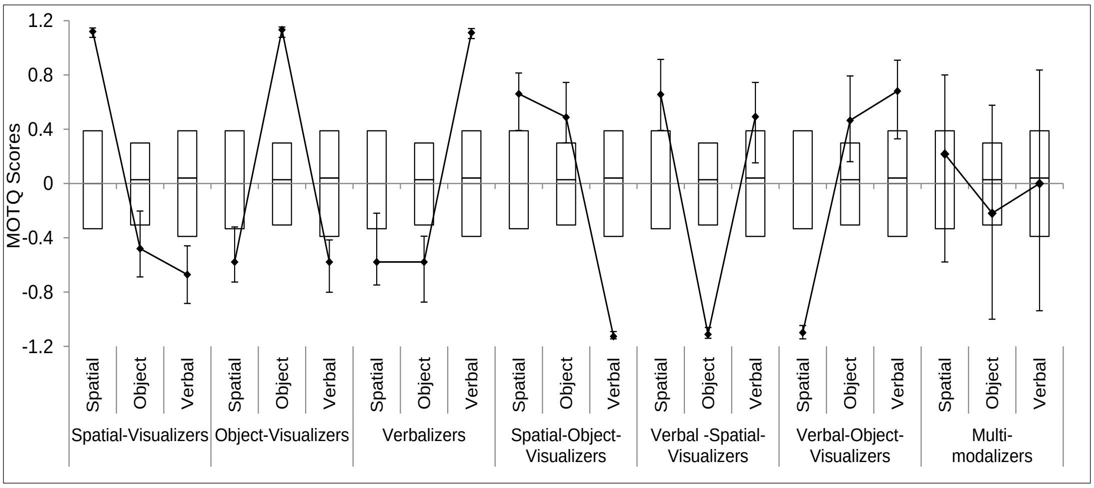


*Figure 4.* MOTQ scores (z-transformed) of the 7 MOTQ types: spatial-visualizers (n=51, 11%), object-visualizers (n=43, 9%), verbalizers (n=86, 18%), spatial-object-visualizers (n=95, 20%), verbal-spatial-visualizers (60, 13%), verbal-object-visualizers (84, 18%), and multi-modalizers (49, 10%). Medians are represented by diamonds, first and third quartiles by upper and lower error bars, respectively. Medians, first and third quartiles of the whole sample (N = 468) are represented by the boxes (middle border, bottom border, and top border, respectively).

**Re-test reliability of MOTQ types.** The correspondence of the MOTQ type from time point #1 to time point #2 was significant (8-week interval, $p < .001$, $N = 197$) but only of moderate strength (Cohen's $\kappa = .52$) according to the guidelines of Landis and Koch (1977). Of all 197 participants who completed the MOTQ 2, only 59% were categorized as the same MOTQ type across the two time points. However, further investigating the 41% of participants who did change MOTQ type from time point #1 to time point #2, reveals that 56% of these participants changed to a neighboring MOTQ type, that is a type which is characterized by comparably higher scores in the same dimension (e.g. for spatial-visualizers neighbors would be spatial-object-visualizers and verbal-spatial-visualizers) or one of the same dimensions (e.g. for a spatial-object-visualizers neighbors would be spatial-visualizers and object-visualizers). 18% changed from a specific MOTQ type (all except multi-modalizers) to the multi-modalizer MOTQ type, 19% from the multi-modalizer to a specific MOTQ type, and only 8% changed to a completely unrelated MOTQ type. Therefore, in sum, of all participants 82% stayed either in the same or changed to a neighboring cluster, 15%

changed from or to the multi-modalizer cluster and only 3% changed to a completely unrelated cluster. The MOTQ types of participants at the two time points are listed in Supplementary Material Appendix I.

**External validity of MOTQ types.** MOTQ types and VVIQ. A one-way ANOVA revealed a significant effect of MOTQ type on VVIQ ($F = 11.425$, $p < .001$). The post-hoc analysis (Table 4) showed that vividness of visual imagery was highest for those MOTQ types characterized by high object scores and lowest for those MOTQ types characterized by low object scores.

***MOTQ types and gender differences.*** The distribution of MOTQ types differed significantly between men and women ($\chi2 = 66.64$, $df = 6$, $\varphi = .377$, $p(\varphi) < .001$). The respective distributions are illustrated in Figure 5. Of those MOTQ types that score high on one and low on the other two MOTQ scales, spatial-visualizers were predominantly men, whereas verbalizers and object-visualizers were predominantly women. The number of object-visualizers in men was very low (4.8%). Of those MOTQ types that scored high on two and low on the third MOTQ scale, verbal-spatial-visualizers were predominantly men, whereas verbal-object-visualizers were predominantly women. About as many men as women were categorized as object-spatial-visualizers or as multi-modalizers.

*Table 4*

Post-hoc Ryan-Einot-Gabriel-Welsch Table of the Effect of MOTQ Type on the VVIQ. MOTQ Types Ordered by Mean Scores on the VVIQ.

| MOTQ type | *n* | 1 | 2 | 3 |
|---|---|---|---|---|
| Verbal-Spatial-Visualizers | 37 | 3.21 | | |
| Verbalizers | 55 | 3.41 | | |
| Spatial-Visualizers | 19 | 3.56 | 3.56 | |
| Multi-Modalizers | 30 | | 3.84 | 3.84 |
| Verbal-Object-Visualizers | 63 | | 3.90 | 3.90 |
| Object-Visualizers | 32 | | | 4.01 |
| Spatial-Object-Visualizers | 55 | | | 4.08 |
| *p* | | .413 | .448 | .640 |

*Note.* MOTQ types whose means are aligned below different numbers (1, 2 or 3) are significantly different from one another ($p <. 20$, $N = 291$). The $p$ values below express at which alpha level, the three groups would need to be further divided.

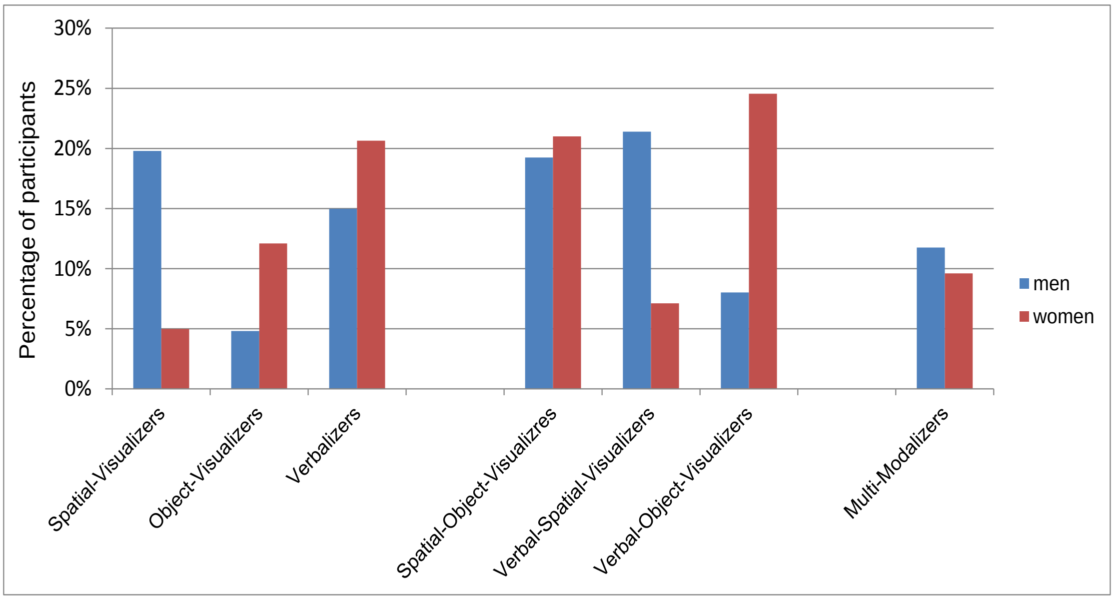


*Figure 5.* Distribution of MOTQ type by gender (N = 468).

***MOTQ types and degree program.*** There was a significant interaction between degree program and MOTQ type ($\chi 2 = 105.58$, df = 12, $\varphi = .49$, $p(\varphi) < .001$). In degree programs with high demands in language such as the humanities (including philosophy, religion, linguistics, history and law) participants were predominantly MOTQ types associated with verbalization, namely verbalizers and verbal-object-visualizers (see Figure 6). In degree programs with high demands in formal and natural sciences (including chemistry, biology, physics, engineering, mathematics) participants were predominantly MOTQ types associated with spatial-visualization, namely spatial-visualizers, spatial-object-visualizers, and verbal-spatial-visualizers. In degree programs with very heterogeneous demands such as the social sciences (including psychology, sociology, economics and politics) MOTQ types were distributed more equally. However, a larger percentage of the students of the social sciences were MOTQ types with high scores in two MOTQ scales (53%) such as object-spatial-visualizers and object-verbalizers as compared to MOTQ types with high scores in only one MOTQ scale (35%).

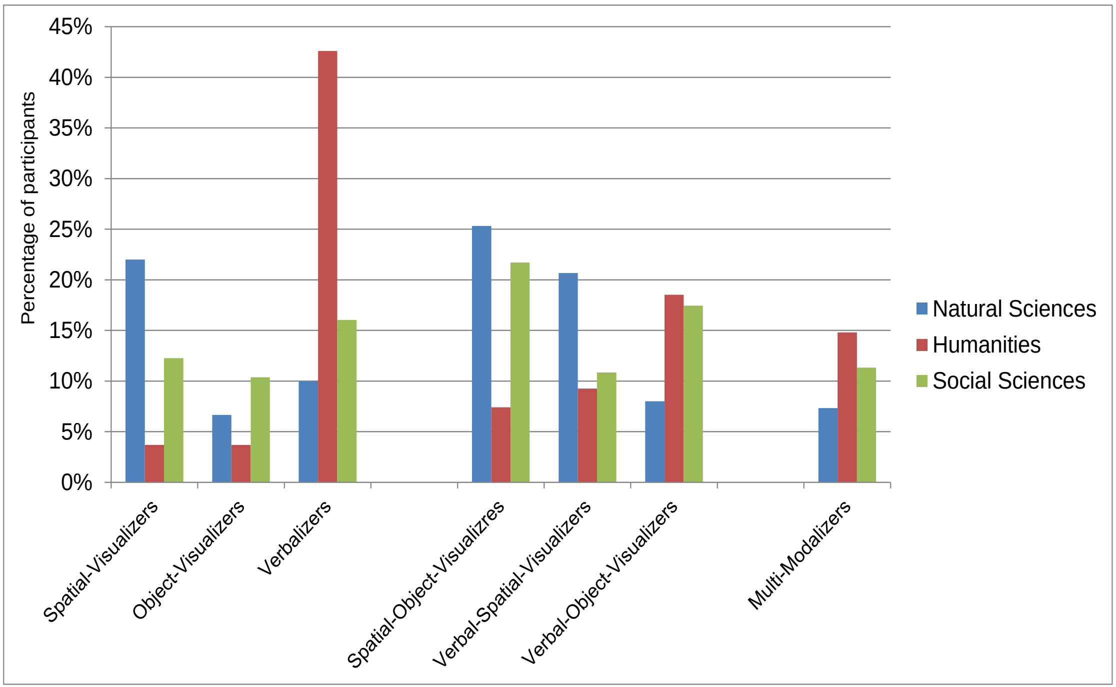


*Figure 6.* Distribution of MOTQ type by degree program (N = 448).

### 2.1.5 Discussion

***Evaluation of the MOTQ***

The MOTQ revealed a very satisfactory three-factor structure, as well as high internal and retest-reliability of the three scales. These results support the two implications of the object-spatial-verbal cognitive style model (Blazhenkova & Kozhevnikov, 2009) (1) to distinguish between object and spatial-visualization and (2) to assess the three dimensions with separate unipolar scales. The high retest reliability over a two-month time period is congruent with previous findings of shorter time intervals (Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009; Chabris et al., 2006) that suggest that the visual-verbal cognitive style represents a stable trait that is resistant to change over time, as would be expected for a cognitive style (Ausburn & Ausburn, 1978). Associations with object-visual ability, degree programs, and gender supported the congruent and discriminant validity of the MOTQ and were in line with the previous literature (Blajenkova et al., 2006; Halpern & LaMay, 2000; Kozhevnikov et al., 2005; Linn & Petersen, 1985; McKelvie, 1995; for a critical review see J. T. Richardson, 1995; Voyer, Voyer, & Bryden, 1995).

***Comparison to the OSIVQ***

Similar to the MOTQ, the OSIVQ showed a three-factor structure, as well as satisfactory internal and external validity. However, factor loadings of exploratory principal component analyses, item-to-scale correlations, and model fits of structural equation modelling suggest a superior factorial structure of the MOTQ. For the MOTQ, all items loaded highest on the factor they were designed to assess (all except 2 items with $r > .4$), no item had a strong negative loading ($r < -.4$) on an undesired factor, and no item had a low ($r < .3$) item-to-scale correlation. For the OSIVQ, 12 items did not load highest on the factor they were designed to assess, 15 items had low loadings ($r > .4$) on the desired factor, 8 items had strong negative loadings ($r < -.4$) on an undesired factor, and 5 items had low ($r < .3$) item-to-scale correlations. For the three factor model suggested by the object-spatial-verbal cognitive style model, confirmatory principal component analysis model fits were also superior for the MOTQ compared to the OSIVQ as indicated by its larger CFI (.70 vs. .60) and lower RMSEA (.08 vs. .10) score. Moreover, a multi-trait multi-method model that accounts for the substructure of the MOTQ with its three subscales for learning, habit, and ability lead to an even better model fit (CFI = 0.84, RMSEA = 0.06).

Inspecting the OSIVQ item texts of those items with strong negative loadings on undesired factors revealed that the respective items are all items that force the participant to make a choice between two dimensions, even though their scoring is treated as if they arbitrarily belonged to only one. Integrating only truly unipolar items as stressed in the development of the MOTQ apparently avoids such artificial negative interrelations.

Regarding external validity, the advantage of the MOTQ is that it does not comprise these artificial negative correlations between its scales (which also led to respective negative correlations between the OSIVQ and non-corresponding MOTQ scales) and that it is less biased towards measuring self-reported ability. The self-reported ability bias of the OSIVQ is reflected by the strong correlations of the OSIVQ scales with the ability subscales of the MOTQ and its high correlation with object visual imagery ability which in the MOTQ was particular to the MOTQ object ability subscale.

### *Cluster Analysis*

Our cluster analysis revealed that individuals can be clustered into seven types based on their MOTQ scores: spatial-visualizers, object-visualizers, verbalizers, spatial-object-visualizers, verbal-spatial-visualizers, verbal-object-visualizers, and multi-modalizers. The distribution of these types suggests that any combination of high and low scores in the three dimensions is empirically possible and thus strongly supports the premise of the new object-spatial-verbal cognitive style model to assess visual-verbal cognitive style with three independent, unipolar scales (Blazhenkova & Kozhevnikov, 2009). The large number of spatial-object–visualizers further illustrates that a strong spatial-visualizer need not be a weak object-visualizer and vice versa, as may have been suggested by previous studies who classified visualizers as either spatial- or object-visual (e.g. Kozhevnikov et al., 2005). Furthermore, a considerable number of participants were categorized as multi-modalizers that apparently show no clear preference of one or two visual-verbal cognitive style dimensions over another. Further investigations must evaluate whether individuals of this type truly use all cognitive style dimensions about equally. A number of individuals might also have difficulty identifying with any of the three dimensions. The scores of ten percent of our participants were below average on all three dimensions and the scores of one percent of our participants were in the lowest quadrant of the sample distribution on all three dimensions.

The test-re-test reliability of the 7 MOTQ types across the eight-week interval was of moderate size. However, a considerable number of participants (82%) stayed either in the same or a neighboring cluster or changed from or to the multi-modalizer cluster (15%). Only 3% changed to a completely unrelated cluster. These results suggest that clustering participants into types may be useful and reliable but participants lying between two clusters may be categorized as one type at one time point and as the other at another. Future studies must establish whether a modified clustering procedure might improve type reliabilities or whether the evaluation of the highly reliable individual MOTQ scores on the three scales are generally to be preferred.

Analogous to the MOTQ scales, the measures used to assess the external validity of the MOTQ types supported their congruent and divergent validity.

### *General Discussion*

The present work proposed the new Modality of Thinking Questionnaire (MOTQ) as an instrument to assess the three dimensions of the object-spatial-verbal cognitive style model and demonstrated its superiority with regard to factorial structure and validity over the Object-Spatial Imagery and Verbal Questionnaire (OSIVQ), the only other questionnaire built upon this model. Based on this new questionnaire, individuals could be categorized into seven types of Visual-Verbal cognitive style. These MOTQ types were of moderate stability and high external validity.

A question repeatedly discussed in the literature (e.g. Blazhenkova & Kozhevnikov, 2009; Kozhevnikov, 2007) concerns the investigation of factors that affect the development of visual-verbal cognitive style. According to Messick (1976, pp. 4-6), cognitive styles are “not simple habits… they develop slowly and experientially and do not appear to be easily modified by specific tuition or training.” In agreement with Messick, we found for visual-verbal cognitive style high retest reliability over a two-month period. However, we also observed a strong effect of degree program on visual-verbal cognitive style. As reported by others, our results show that individuals have the propensity to acquire, process, and represent information in accordance with the demands of their discipline, not only once they work in a certain profession (Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009; Isaac & Marks, 1994) but during prior education (Blazhenkova & Kozhevnikov, 2009; Isaac & Marks, 1994). These associations were reflected by the correlations of MOTQ scales and types with the primary demands of their degree program and the relatively larger prominence of students in degree programs of heterogonous compared to homogeneous demands in MOTQ types comprising high scores in two rather than solely one dimension. The large percentage of students in our sample (51%) who were only in their first or second year at university further suggests that either the discipline-specific visual-verbal cognitive style had already largely developed prior to university entrance and possibly motivated the choice of the degree program or had very quickly been promoted by the demands of the degree program. It would be interesting to further investigate the causality and interrelationship between visual-verbal cognitive style and choice of degree program. Is the cognitive style a predictor of degree program choice and / or the success in a given degree program, or does the cognitive style only develop or at least strongly intensify during the course of studies in a particular domain?

Furthermore, how do they relate to our observed gender differences? A large body of literature investigated cognitive abilities and gender. However, to understand their development, it may be worth considering that early preferences to think in a particular modality may play a fundamental role in their facilitation. In our sample, men showed higher spatial but lower object scores than women, whilst there was no significant difference between genders in absolute verbal scores but a predominance of women in MOTQ types with comparably high verbalization scores such as verbalizers and verbal-object-visualizers. Previous studies have failed to show verbal cognitive style differences between genders (Blazhenkova & Kozhevnikov, 2009), however verbal ability differences have frequently been reported (for a review see: Halpern & LaMay, 2000). Possibly differences between ability and cognitive style are more pronounced in the verbalization dimension than in the visual dimensions and gender differences in verbal cognitive style may only become apparent when individuals' profiles (relative preferences) are investigated rather than solely their absolute scores. Longitudinal studies assessing both visual-verbal ability and cognitive style profiles from an early age on are needed to learn more about these interrelations.

Beyond the scientific investigation of individuals' cognitive development and inter-individual differences, potential fields of application of the MOTQ are numerous. Cognitive styles have been reported to predict academic achievement and individuals' success beyond general abilities (Zhang & Sternberg, 2014) and have been considered relevant for individual and organizational behavior (e.g. Sadler-Smith, 2011; Streufert & Nogami, 1989; Talbot, 1989). Therefore, their field of application may range from the domains of pedagogics, career counselling, personnel selection, internal communications, to that of conflict management (Hayes & Allinson, 1994; see also Kozhevnikov, 2007). It remains to be investigated how far these disciplines can profit from the assessment and integration of visual-verbal cognitive style as assessed by the MOTQ in particular.

Even though the premises of the new object-spatial-verbal cognitive style model were based on findings from neuropsychology, neuroimaging studies investigating differences between individuals with varying visual-verbal cognitive styles are scarce (Miller, Donovan, Bennett, Aminoff, & Mayer, 2012; Motes & Kozhevnikov, 2006). The results of Motes and Kozhevnikov (2006) suggested that spatial-visualizers showed stronger left-hemispheric occipito-temporal activation, whereas object-visualizers showed stronger bilateral occipito-parietal activation during the execution of a spatial-ability task. This finding is consistent with the hypothesis of a style-based use of the dorsal and the ventral visual processing streams. However, more neuroimaging studies are needed to validate these results. Moreover, one could expect that visual-verbal cognitive style differences cannot only be observed during task execution but also during no-task resting. Functional magnetic resonance imaging and electroencephalography studies on the default state have identified networks associated with visual and verbal / phonological processing respectively (Britz et al., 2010; Milz et al., submitted). It remains to be seen whether the differential activation of these networks depends on an individual's visual-verbal cognitive style.

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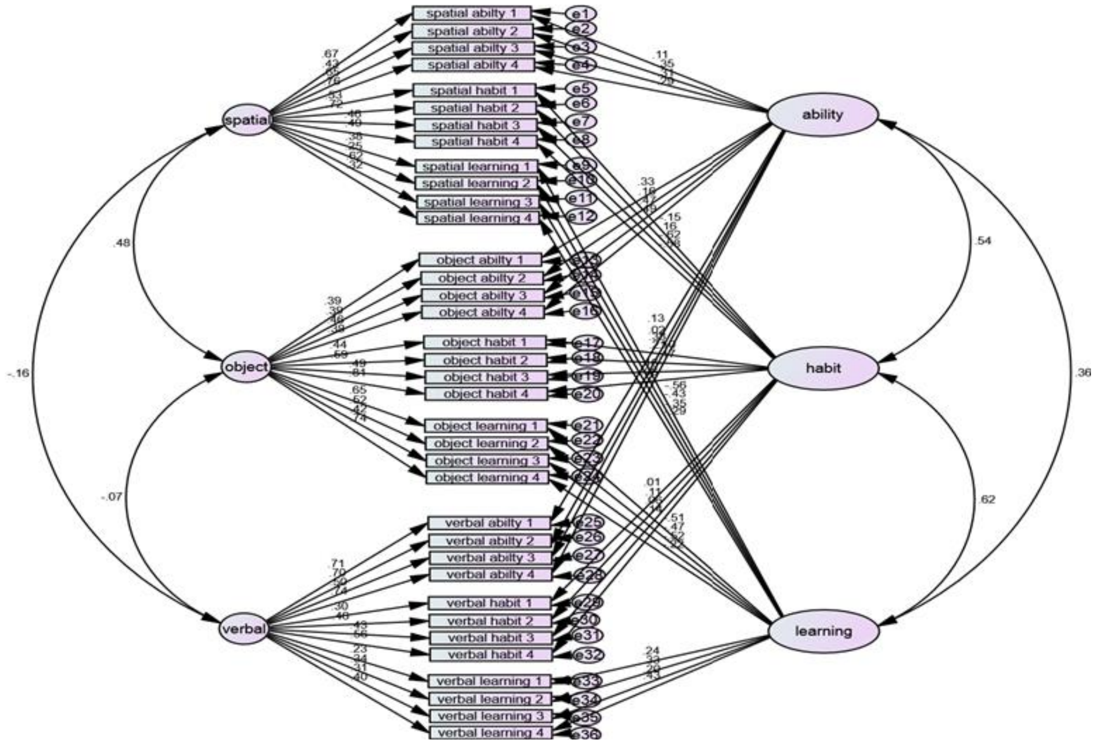
### 2.1.8 Supplementary Material

Appendix A

Visualization of the MOTQ model 5 (multi-trait multi-method model). The numbers above the arrows indicate the standardized factor loadings.



Appendix B

Differential Goodness-of-Fit Indices for nested MOTQ and OSVIQ models.

| Questionnaire | MOTQ | | | OSIVQ | | |
|---|---|---|---|---|---|---|
| Model comparison | $\chi2$ | *df* | *p* | $\chi2$ | *df* | *p* |
| Model 1 vs Model 2 | 881 | 1 | <.001 | 641 | 1 | <.001 |
| Model 2 vs Model 3 | 740 | 2 | <.001 | 284 | 2 | <.001 |
| Model 3 vs Model 4 | 456 | 9 | <.001 | | | |
| Model 4 vs Model 5 | 396 | 30 | <.001 | | | |

Appendix C

Cronbach’s Alpha and re-test reliability of the MOTQ subscales.

| Scales | Subscales | Cronbach’s α | Re-test reliability |
|---|---|---|---|
| Spatial | Learning | .68 | .71 |
| | Habit | .70 | .75 |
| | Ability | .76 | .85 |
| Object | Learning | .81 | .83 |
| | Habit | .70 | .78 |
| | Ability | .67 | .80 |
| Verbal | Learning | .59 | .70 |
| | Habit | .57 | .72 |
| | Ability | .79 | .86 |

Appendix D

Convergent and Divergent Validity as the Correlation between the VVIQ and the Scales and Subscales of the MOTQ 1 (N = 291) and MOTQ 2 (N = 167).

| | MOTQ 1 | | | | MOTQ 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | Scales | Subscales | | | Scales | Subscales | | |
| | | Learning | Habit | Ability | | Learning | Habit | Ability |
| Spatial | .28* | .21* | .25* | .25* | .23* | .08 | .30* | .23* |
| Object | .67* | .42* | .60* | .62* | .68* | .44* | .64* | .70* |
| Verbal | .10 | -.02 | .09 | .15* | .04 | -.15* | .15 | .10 |

*Note.* *$p$ < .05.

Appendix E

Univariate effects of gender on MOTQ1, MOTQ2, and OSIVQ scales.

| Dependent variable | | *df* | *df* error | *F* | *p* | Partial η2 | Gender | *M* | 95% Confidence Interval Lower Bound | Upper Bound |
|---|---|---|---|---|---|---|---|---|---|---|
| MOTQ 1 | Spatial | 1 | 466 | 59.410 | >0.001 | 0.11 | Male | 3.76 | 0.344 | 0.579 |
| | | | | | | | Female | 3.30 | 0.348 | 0.576 |
| | Object | 1 | 466 | 11.981 | 0.001 | 0.03 | Male | 3.32 | -0.344 | -0.095 |
| | | | | | | | Female | 3.54 | -0.346 | -0.092 |
| | Verbal | 1 | 466 | 0.011 | 0.917 | 0.00 | Male | 3.49 | -0.111 | 0.123 |
| | | | | | | | Female | 3.48 | -0.108 | 0.120 |
| MOTQ 2 | Spatial | 1 | 195 | 8.634 | 0.004 | 0.04 | Male | 3.79 | 0.139 | 0.704 |
| | | | | | | | Female | 3.37 | -0.704 | -0.139 |
| | Object | 1 | 195 | 7.872 | 0.006 | 0.04 | Male | 3.07 | -0.760 | -0.133 |
| | | | | | | | Female | 3.51 | 0.133 | 0.760 |
| | Verbal | 1 | 195 | 0.519 | 0.472 | 0.00 | Male | 3.63 | -0.157 | 0.337 |
| | | | | | | | Female | 3.54 | -0.337 | 0.157 |
| OSIVQ | Spatial | 1 | 159 | 19.761 | >0.001 | 0.11 | Male | 3.51 | 0.394 | 1.023 |
| | | | | | | | Female | 2.80 | 0.391 | 1.026 |
| | Object | 1 | 159 | 14.276 | >0.001 | 0.08 | Male | 2.72 | -0.952 | -0.298 |
| | | | | | | | Female | 3.35 | -0.986 | -0.264 |
| | Verbal | 1 | 159 | 0.556 | 0.457 | 0.00 | Male | 3.28 | -0.181 | 0.401 |
| | | | | | | | Female | 3.17 | -0.152 | 0.372 |

## Appendix F

Univariate effects of degree program on MOTQ 1, MOTQ 2, and OSIVQ scales and Games Howell t-tests between degree programs (Nat: Natural Sciences, Hum: Humanities, Soc: Social Sciences).

| Dependent variable | | *df* | *df* error | *F* | *p* | Partial η2 | Degree Progam (i) | Degree Progam (j) | Mean Diff-erence (i-j) | *SE* | Games Howell *p* | 95% Confidence Interval | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Lower Bound | Upper Bound |
| MOTQ 1 | Spatial | 2 | 444 | 44.71 | <0.001 | 0.17 | Nat | Hum | 0.76 | 0.08 | <.001 | 0.559 | 0.956 |
| | | | | | | | | Soc | 0.42 | 0.06 | <.001 | 0.266 | 0.567 |
| | | | | | | | Hum | Nat | -0.76 | 0.08 | <.001 | -0.956 | -0.559 |
| | | | | | | | | Soc | -0.34 | 0.08 | <.001 | -0.537 | -0.145 |
| | | | | | | | Soc | Nat | -0.42 | 0.06 | <.001 | -0.567 | -0.266 |
| | | | | | | | | Hum | 0.34 | 0.08 | <.001 | 0.145 | 0.537 |
| | Object | 2 | 444 | 9.21 | <0.001 | 0.04 | Nat | Hum | 0.15 | 0.09 | 0.188 | -0.052 | 0.352 |
| | | | | | | | | Soc | -0.19 | 0.07 | 0.018 | -0.352 | -0.026 |
| | | | | | | | Hum | Nat | -0.15 | 0.09 | 0.188 | -0.352 | 0.052 |
| | | | | | | | | Soc | -0.34 | 0.08 | <.001 | -0.533 | -0.145 |
| | | | | | | | Soc | Nat | 0.19 | 0.07 | 0.018 | 0.026 | 0.352 |
| | | | | | | | | Hum | 0.34 | 0.08 | <.001 | 0.145 | 0.533 |
| | Verbal | 2 | 444 | 22.39 | <0.001 | 0.09 | Nat | Hum | -0.54 | 0.07 | <.001 | -0.718 | -0.367 |
| | | | | | | | | Soc | -0.20 | 0.07 | 0.009 | -0.360 | -0.041 |
| | | | | | | | Hum | Nat | 0.54 | 0.07 | <.001 | 0.367 | 0.718 |
| | | | | | | | | Soc | 0.34 | 0.07 | <.001 | 0.184 | 0.500 |
| | | | | | | | Soc | Nat | 0.20 | 0.07 | 0.009 | 0.041 | 0.360 |
| | | | | | | | | Hum | -0.34 | 0.07 | <.001 | -0.500 | -0.184 |
| MOTQ 2 | Spatial | 2 | 190 | 10.78 | <0.001 | 0.10 | Nat | Hum | 0.71 | 0.17 | <.001 | 0.306 | 1.122 |
| | | | | | | | | Soc | 0.40 | 0.11 | 0.001 | 0.141 | 0.669 |
| | | | | | | | Hum | Nat | -0.71 | 0.17 | <.001 | -1.122 | -0.306 |
| | | | | | | | | Soc | -0.31 | 0.15 | 0.124 | -0.684 | 0.066 |
| | | | | | | | Soc | Nat | -0.40 | 0.11 | 0.001 | -0.669 | -0.141 |
| | | | | | | | | Hum | 0.31 | 0.15 | 0.124 | -0.066 | 0.684 |
| | Object | 2 | 190 | 6.91 | 0.001 | 0.07 | Nat | Hum | 0.27 | 0.18 | 0.301 | -0.162 | 0.698 |
| | | | | | | | | Soc | -0.27 | 0.14 | 0.131 | -0.592 | 0.059 |
| | | | | | | | Hum | Nat | -0.27 | 0.18 | 0.301 | -0.698 | 0.162 |
| | | | | | | | | Soc | -0.53 | 0.15 | 0.003 | -0.905 | -0.163 |
| | | | | | | | Soc | Nat | 0.27 | 0.14 | 0.131 | -0.059 | 0.592 |
| | | | | | | | | Hum | 0.53 | 0.15 | 0.003 | 0.163 | 0.905 |
| | Verbal | 2 | 190 | 4.70 | 0.010 | 0.05 | Nat | Hum | -0.41 | 0.15 | 0.022 | -0.768 | -0.049 |
| | | | | | | | | Soc | -0.11 | 0.12 | 0.634 | -0.384 | 0.173 |
| | | | | | | | Hum | Nat | 0.41 | 0.15 | 0.022 | 0.049 | 0.768 |
| | | | | | | | | Soc | 0.30 | 0.12 | 0.039 | 0.012 | 0.593 |
| | | | | | | | Soc | Nat | 0.11 | 0.12 | 0.634 | -0.173 | 0.384 |
| | | | | | | | | Hum | -0.30 | 0.12 | 0.039 | -0.593 | -0.012 |

| Dependent variable | | *df* | *df* error | *F* | *p* | Partial η2 | Degree Progam (i) | Degree Progam (j) | Mean Diff-erence (i-j) | *SE* | Games Howell *p* | 95% Confidence Interval | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Lower Bound | Upper Bound |
| OSIVQ | Spatial | 2 | 155 | 6.68 | 0.002 | 0.08 | Nat | Hum | 0.56 | 0.20 | 0.017 | 0.085 | 1.040 |
| | | | | | | | | Soc | 0.51 | 0.16 | 0.007 | 0.122 | 0.893 |
| | | | | | | | Hum | Nat | -0.56 | 0.20 | 0.017 | -1.040 | -0.085 |
| | | | | | | | | Soc | -0.05 | 0.15 | 0.931 | -0.424 | 0.314 |
| | | | | | | | Soc | Nat | -0.51 | 0.16 | 0.007 | -0.893 | -0.122 |
| | | | | | | | | Hum | 0.05 | 0.15 | 0.931 | -0.314 | 0.424 |
| | Object | 2 | 155 | 3.29 | 0.040 | 0.04 | Nat | Hum | -0.21 | 0.19 | 0.499 | -0.660 | 0.238 |
| | | | | | | | | Soc | -0.39 | 0.15 | 0.027 | -0.738 | -0.038 |
| | | | | | | | Hum | Nat | 0.21 | 0.19 | 0.499 | -0.238 | 0.660 |
| | | | | | | | | Soc | -0.18 | 0.16 | 0.514 | -0.562 | 0.209 |
| | | | | | | | Soc | Nat | 0.39 | 0.15 | 0.027 | 0.038 | 0.738 |
| | | | | | | | | Hum | 0.18 | 0.16 | 0.514 | -0.209 | 0.562 |
| | Verbal | 2 | 155 | 4.95 | 0.008 | 0.06 | Nat | Hum | -0.38 | 0.17 | 0.064 | -0.782 | 0.018 |
| | | | | | | | | Soc | 0.02 | 0.15 | 0.991 | -0.339 | 0.377 |
| | | | | | | | Hum | Nat | 0.38 | 0.17 | 0.064 | -0.018 | 0.782 |
| | | | | | | | | Soc | 0.40 | 0.12 | 0.003 | 0.122 | 0.681 |
| | | | | | | | Soc | Nat | -0.02 | 0.15 | 0.991 | -0.377 | 0.339 |
| | | | | | | | | Hum | -0.40 | 0.12 | 0.003 | -0.681 | -0.122 |

## Appendix G

Convergent Validity Measured as the Correlation between the MOTQ Scales and Subscales and the Corresponding OSIVQ Scales (N = 161).

| Questionnaire | | MOTQ 1 | | | | MOTQ 2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Scales | Subscales | | | Scales | Subscales | | |
| | | | Learning | Habit | Ability | | Learning | Habit | Ability |
| OSIVQ | Spatial | .71* | .56* | .57* | .68* | .73* | .67* | .56* | .68* |
| | Object | .79* | .48* | .76* | .73* | .80* | .51* | .78* | .78* |
| | Verbal | .73* | .50* | .52* | .71* | .76* | .52* | .51* | .74* |

*Note.* *$p < .05$.

Appendix H

Divergent Validity as the Correlation between MOTQ Scales and the Non-corresponding OSIVQ scales (N = 161).

| Questionnaire | | MOTQ 1 | | | MOTQ 2 | | |
|---|---|---|---|---|---|---|---|
| | Scale | Spatial | Object | Verbal | Spatial | Object | Verbal |
| OSIVQ | Spatial | | -.25* | -.31* | | -.11 | -.29* |
| | Object | .10 | | .11 | .15 | | .14 |
| | Verbal | -.42* | -.22* | | -.38* | -.29* | |

*Note*. *$p < .05$.

# Appendix I

Cross-tab of the MOTQ 1 and MOTQ 2 Cluster Memberships of the Participants Who Took Part at Both Assessment Time Points (N = 197).

| | | | MOTQ 2 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | MOTQ Type | | Spatial-Visualizers | Object-Visualizers | Verbalizers | Spatial-Object-Visualizers | Verbal-Spatial-Visualizers | Verbal-Object-Visualizers | Multi-Modalizers | Total |
| MOTQ 1 | Spatial-Visualizers | Count | 9 | 0 | 0 | 1 | 1 | 0 | 1 | 12 |
| | | % within | 75%[a] | 0% | 0% | 8% | 8% | 0% | 8% | 100% |
| | Object-Visualizers | Count | 1 | 11 | 0 | 6 | 0 | 2 | 5 | 25 |
| | | % within | 4% | 44%[a] | 0% | 24% | 0% | 8% | 20% | 100% |
| | Verbalizers | Count | 0 | 1 | 26 | 0 | 5 | 1 | 2 | 35 |
| | | % within | 0% | 3% | 74%[a] | 0% | 14% | 3% | 6% | 100% |
| | Spatial-Object-Visualizers | Count | 2 | 4 | 1 | 28 | 1 | 1 | 1 | 38 |
| | | % within | 5% | 11% | 3% | 74%[a] | 3% | 3% | 3% | 100% |
| | Verbal-Spatial-Visualizers | Count | 1 | 1 | 5 | 0 | 12 | 0 | 1 | 20 |
| | | % within | 5% | 5% | 25% | 0% | 60%[a] | 0% | 5% | 100% |
| | Verbal-Object-Visualizers | Count | 0 | 8 | 9 | 0 | 0 | 27 | 5 | 49 |
| | | % within | 0% | 16% | 18% | 0% | 0% | 55%[a] | 10% | 100% |
| | Multi-Modalizers | Count | 8 | 3 | 0 | 0 | 1 | 2 | 4 | 18 |
| | | % within | 44% | 17% | 0% | 0% | 6% | 11% | 22%[a] | 100% |
| Total | | Count | 21 | 28 | 41 | 35 | 20 | 33 | 19 | 197 |
| | | % within | 10.7% | 14.2% | 20.8% | 17.8% | 10.2% | 16.8% | 9.6% | 100.0% |

[a]The percentage of participants who stayed in the same cluster across the two time points.

## 2.2 Manuscript 2 (published)

## The Functional Significance of EEG Microstates – Associations with Modalities of Thinking[16]

### 2.2.1 Abstract

The momentary, global functional state of the brain is reflected by its electric field configuration. Cluster analytical approaches consistently extracted four head-surface brain electric field configurations that optimally explain the variance of their changes across time in spontaneous EEG recordings. These four configurations are referred to as EEG microstate classes A, B, C, and D and have been associated with verbal / phonological, visual, subjective interoceptive-autonomic processing, and attention reorientation, respectively. The present study tested these associations via an intra-individual and inter-individual analysis approach. The intra-individual approach tested the effect of task-induced increased modality-specific processing on EEG microstate parameters. The inter-individual approach tested the effect of personal modality-specific parameters on EEG microstate parameters.

We obtained multichannel EEG from 61 healthy, right-handed, male students during four eyes closed conditions: object-visualization, spatial-visualization, verbalization (6 runs each), and resting (7 runs). After each run, we assessed participants' degrees of object-visual, spatial-visual, and verbal thinking using subjective reports. Before and after the recording, we assessed modality-specific cognitive abilities and styles using nine cognitive tests and two questionnaires. The EEG of all participants, conditions, and runs was clustered into four classes of EEG microstates (A, B, C, and D). RMANOVAs, ANOVAs and post-hoc paired t-tests compared microstate parameters between conditions. TANOVAs compared microstate class topographies between conditions. Differences were localized using eLORETA. Pearson correlations assessed interrelationships between personal modality-specific parameters and EEG microstate parameters during no-task resting.

[16] At time of print, this manuscript is published in: Milz, P., Faber, P. L., Lehmann, D., Koenig, T., Kochi, K., & Pascual-Marqui, R. D. (2016). The functional significance of EEG microstates – associations with modalities of thinking. *Neuroimage*, 125, 643-56. doi:10.1016/j.neuroimage.2015.08.023

As hypothesized, verbal as opposed to visual conditions consistently affected the duration, occurrence, and coverage of microstate classes A and B. Contrary to associations suggested by previous reports, parameters were increased for class A during visualization, and class B during verbalization. In line with previous reports, microstate D parameters were increased during no-task resting compared to the three internal, goal-directed tasks. Topographic differences between conditions included particular sub-regions of components of the metabolic default mode network. Modality-specific personal parameters did not consistently correlate with microstate parameters except verbal cognitive style which correlated negatively with microstate class A duration and positively with class C occurrence.

This is the first study that aimed to induce EEG microstate class parameter changes based on their hypothesized functional significance. Beyond, the associations of microstate classes A and B with visual and verbal processing, respectively, our results suggest that a finely-tuned interplay between all four EEG microstate classes is necessary for the continuous formation of visual and verbal thoughts. Our results point to the possibility that the EEG microstate classes may represent the head-surface measured activity of intra-cortical sources primarily exhibiting inhibitory functions. However, additional studies are needed to verify and elaborate on this hypothesis.

## 2.3 Manuscript 3 (published)

**Modalities of Thinking: State and Trait Effects on Cross-Frequency Functional Independent Brain Networks**[17]

### 2.3.1 Abstract

Functional states of the brain are constituted by the temporally attuned activity of spatially distributed neural networks. Such networks can be identified by independent component analysis (ICA) applied to frequency-dependent source-localized EEG data. This methodology allows the identification of networks at high temporal resolution in frequency bands of established location-specific physiological functions. EEG measurements are sensitive to neural activity changes in cortical areas of modality-specific processing. We tested effects of modality-specific processing on functional brain networks. Phasic modality-specific processing was induced via tasks (state effects) and tonic processing was assessed via modality-specific person parameters (trait effects).

Modality-specific person parameters and 64-channel EEG were obtained from 70 male, right-handed students. Person parameters were obtaind using cognitive style questionnaires, cognitive tests, and thinking modality self-reports. EEG was recorded during four conditions: spatial visualization, object visualization, verbalization, and resting. Twelve cross-frequency networks were extracted from source-localized EEG across six frequency bands using ICA. RMANOVAs, Pearson correlations, and path modelling examined effects of tasks and person parameters on networks.

Results identified distinct state- and trait-dependent functional networks. State-dependent networks were characterized by decreased, trait-dependent networks by increased alpha activity in sub-regions of modality-specific pathways. Pathways of competing modalities showed opposing alpha changes. State- and trait-dependent alpha were associated with inhibitory and automated processing, respectively. Antagonistic alpha modulations in areas of competing modalities likely prevent intruding effects of modality-irrelevant processing.

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[17] At time of print, this manuscript is published in: Milz, P., Pascual-Marqui, R. D., Lehmann, D., Faber, P. L. (2016). Modalities of thinking: state and trait effects on cross-frequency functional independent brain networks. *Brain Topography*. Advance online publication. doi:10.1007/s10548-016-0469-3

Considerable research suggested alpha modulations related to modality-specific states and traits. This study identified the distinct electrophysiological cortical frequency-dependent networks within which they operate.

## 3. Unpublished Results

The following section describes several findings that were not included in the three manuscripts of this thesis but are regarded as relevant for the interpretation of the results. They include results from behavioral and EEG data.

### 3.1 Behavioral

#### 3.1.1 OSIVQ.

***Correlations between Scales***

I inspected the inter-scale correlations of the OSIVQ with the sample of Data Assessment 3. In line with the findings reported in Manuscript 1, two to three scales of the OSIVQ scales were significantly negatively correlated (Table 2).

*Table 2*

Pearson r-values of Correlations between the OSIVQ Scales at the two Assessment Time Points

| | **OSIVQ 1** | | | **OSIVQ 2** | | |
|---|---|---|---|---|---|---|
| **Scales** | **Spatial** | **Object** | **Verbal** | **Spatial** | **Object** | **Verbal** |
| **Spatial** | | -.09 | ***<u>-.43</u>*** | | -.14 | ***<u>-.40</u>*** |
| **Object** | -.09 | | ***<u>-.25</u>*** | -.14 | | -.07 |
| **Verbal** | ***<u>-.43</u>*** | ***<u>-.25</u>*** | | ***<u>-.40</u>*** | -.07 | |

*Note*. *R*-values of significant (*p*<.05 no correction for multiple testing) correlations are highlighted in bold-face, italic, and underlined.

***Reliability***

Manuscript 1 shows that re-test reliabilities were high for the OSIVQ. However, the OSIVQ sample used in Manuscript 1 was strongly unbalanced between genders. There was a large majority of women. Therefore, I used the sample of Data Assessment 3 (men only) to compute re-test reliabilities also for this sample. Re-test reliabilities of the OSIVQ scales were high (r > .89) for the three scales of the OSIVQ. Moderate negative correlations (r<-.37) between the spatial- and verbal scales across time points were also observed.

### *Validity*

**Content validity.** Content validity (also known as logical validity) refers to "how accurately an assessment or measurement tool taps into the various aspects of the specific construct in question. In other words, do the questions really assess the construct in question, or are the responses by the person answering the questions influenced by other factors?" (Clause, 2015).

The OSIVQ intends to measure spatial-object-verbal cognitive style that is an individual's propensity to represent information in a spatial-, object- visual, or verbal format (see Introduction).

An inspection of the OSIVQ items reveals that 14 of the 45 items of the OSIVQ ask for the self-report of a modality-specific ability (5 for spatial, 3 for object, 6 for verbal), 7 for the self-report of another ability (e.g. related to drawing, profession, mechanical, memory; 3 for spatial, 2 for object, 2 for verbal), and 3 ask for profession preferences / interests (2 for spatial, 1 for object). The respective items are shown in Table 3.

For spatial-visual, the remaining 5 items assess the nature of internal images (OSIVQ 5, 12, 13), material type preferences when reading (OSIVQ4), and whether visual imagery is used habitually or only to solve problems (OSIVQ 7). For object-visual, the remaining 9 items ask for art-type preferences (OSIVQ 25), the degree of compulsiveness of internal images (OSIVQ 26), the frequency and habit to visualize (OSIVQ 29, 30), and the nature of internal images (OSIVQ 16, 17, 20, 22, 23). For verbal, the remaining 7 items ask for the enjoyment of word-associated activities (OSIVQ 37, 42, 44), the degree of care about verbal correctness (OSIVQ 43), the habit to remember verbally vs. visually (OSIVQ 40), the habit to verbalize (OSIVQ 38), and visualization habits (OSIVQ 39, recoded use for the verbal scale).

Consequently, less than a third of the 45 OSIVQ items ask about the nature of internal images or the habits to visualize or verbalize as would be expected for a cognitive style measure.

*Table 3*

Description of the Concept Measured by the 45 OSIVQ Items and their Pearson Correlations with Spatial-Visual (Sv), Object-Visual (Ov), and Verbal (Ve) Ability Factors

| OSIVQ | | Ability | | | Item Type | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Scale | # | Sv | Ov | Ve | Ability-Related | Prof-Related | Dicho-tomous | Other | Concept |
| **Spatial** | 1 | **0.50** | 0.17 | -0.11 | yes[1] | | | | self-reported spatial ability (pupil, past) |
| | 2 | **0.28** | -0.07 | -0.15 | | yes | yes[a] | | profession preference |
| | 3 | 0.17 | -0.08 | -0.04 | | yes | yes[a] | | profession interest |
| | 4 | 0.12 | -0.06 | -0.03 | | | yes[a] | | material type preference when reading |
| | 5 | 0.19 | 0.09 | -0.17 | | | yes[a] | | nature of internal images |
| | 6 | **0.36** | 0.03 | 0.17 | yes[1] | | | | self-reported spatial ability (now) |
| | 7 | 0.06 | 0.14 | ***-0.29*** | | | yes[a] | | spontaneous images or task-dependent |
| | 8 | **0.29** | 0.14 | 0.04 | yes[2] | | | | self-reported drawing ability (now) |
| | 9 | **0.38** | 0.13 | -0.06 | yes[1] | | | | self-reported spatial ability (now) |
| | 10 | **0.51** | 0.03 | 0.01 | yes[2] | | | | self-reported drawing ability (now) |
| | 11 | **0.33** | 0.07 | -0.05 | yes[1] | | | | self-reported spatial ability (pupil, past) |
| | 12 | **0.27** | -0.04 | -0.14 | | | yes[a] | | nature of internal images |
| | 13 | 0.18 | 0.03 | -0.04 | | | yes[a] | | nature of internal images |
| | 14 | -0.21 | 0.05 | ***-0.28*** | yes[1] | | | | self-reported spatial ability (now) |
| | 15 | **0.25** | 0.09 | -0.06 | yes[2] | yes | | | self-reported ability profession related |
| **Object** | 16 | ***-0.26*** | 0.14 | -0.04 | | | | yes | nature of internal images |
| | 17 | 0.02 | 0.00 | -0.09 | | | | yes | nature of internal images |
| | 18 | 0.01 | 0.12 | 0.12 | yes[1] | | | | self-reported object ability (now) |
| | 19 | 0.03 | -0.03 | 0.10 | yes[1] | | | | self-reported object ability (now) |
| | 20 | 0.08 | 0.03 | 0.00 | | | | yes | nature of internal images |
| | 21 | -0.13 | 0.07 | 0.05 | | yes | yes[a] | | profession preference |
| | 22 | 0.15 | 0.15 | 0.17 | | | | yes | nature of internal images |
| | 23 | -0.12 | 0.21 | 0.09 | | | | yes | nature of internal images |
| | 24 | -0.07 | 0.10 | 0.10 | yes[1] | | | | self-reported object ability (now) |
| | 25 | ***-0.27*** | **0.43** | -0.11 | | | | yes | art type preference |
| | 26 | 0.00 | 0.14 | -0.06 | | | | yes | compulsiveness of internal images |
| | 27 | 0.12 | -0.02 | -0.01 | yes[2] | | | | self-reported ability (visual memory) |
| | 28 | 0.03 | 0.01 | -0.06 | yes[2] | | yes[b] | | self-reported ability (visual memory) |
| | 29 | 0.01 | 0.07 | -0.02 | | | | yes | frequency of internal images |
| | 30 | -0.06 | 0.08 | 0.02 | | | | yes | visual habit |
| **Verbal** | 31 | 0.22 | 0.02 | -0.15 | yes[1] | | | | self-reported verbal ability (now) |
| | 32 | 0.00 | 0.03 | 0.12 | yes[1] | | | | self-reported verbal ability (now) |
| | 33 | 0.09 | 0.18 | -0.15 | yes[1] | | | | self-reported verbal ability (now) |
| | 34 | -0.20 | -0.10 | **0.39** | yes[2] | yes | | | self-reported ability profession- related |
| | 35 | -0.22 | 0.06 | **0.41** | yes[1] | | | | self-reported verbal ability (now) |
| | 36 | ***-0.37*** | 0.14 | 0.13 | yes[2] | | yes[c] | | self-reported mechanical ability |
| | 37 | ***-0.33*** | -0.20 | 0.14 | | | yes[d] | | preference to use words over drawing |
| | 38 | -0.06 | 0.02 | 0.04 | | | yes[d] | | verbal habit |
| | 39 | 0.00 | -0.07 | 0.07 | | | | yes | spatial and object visual habit |

| OSIVQ | | Ability | | | Item Type | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Scale | # | Sv | Ov | Ve | Ability-Related | Prof-Related | Dicho-tomous | Other | Concept |
| **Verbal** | 40 | *-0.39* | -0.09 | 0.14 | | | yes[d] | | verbal vs. visual habit (memory) |
| | 41 | -0.22 | -0.02 | <u>0.33</u> | yes[1] | | | | self-reported verbal ability (now) |
| | 42 | -0.16 | -0.04 | -0.10 | | | yes[d] | | preference of verbal over visual material |
| | 43 | -0.04 | 0.01 | 0.22 | | | | yes | degree of care about verbal correctness |
| | 44 | *-0.24* | -0.10 | 0.17 | | | | yes | enjoying verbal activities |
| | 45 | 0.14 | 0.08 | *-0.30* | yes[1] | | | | self-reported verbal ability |

*Note.* Correlation coefficients significant at p<.05 (uncorrected) are italic and red (positive) and underlined and blue (negative). yes[1]: spatial, object, verbal ability self-report, yes[2]: other ability self-report (e.g. drawing, mechanical, memory). yes[a] :decision between spatial- and object-visual, yes[b] : decision between object-visual and verbal, yes[c] : decision between spatial-visual and verbal, yes[d]: decision between visual and verbal. Correlations were based on the first assessment of the OSIVQ (N=70). The original OSIVQ items can be found in (Blazhenkova & Kozhevnikov, 2009).

### Construct validity.

***Style and ability.*** Among other measures, the original publication of the OSIVQ (Blazhenkova & Kozhevnikov, 2009) used modality-specific cognitive tests to support the construct validity of the OSIVQ.

I correlated OSIVQ-assessed style and ability for the two assessment time points of Data Assessment 3 (Table 4). Spatial-visual style was moderately correlated with spatial-visual ability. The other two dimensions were not significantly correlated with the respective abilities across assessment time points. However, correlation coefficients were significant for one, and only slightly below the significance threshold for the other assessment time point. The strong negative correlation of verbal style with spatial ability may indicate a lack of discriminant validity and be associated with the dichotomous items used in the OSIVQ.

*Table 4*

Pearson r-values of Correlations between Cognitive Abilities and OSIVQ-Assessed Object-Spatial-Verbal Cognitive Style

| | **OSIVQ 1** | | | **OSIVQ 2** | | |
|---|---|---|---|---|---|---|
| **Ability** | **Spatial** | **Object** | **Verbal** | **Spatial** | **Object** | **Verbal** |
| **Spatial** | ***.53*** | -.06 | ***-.31*** | ***.50*** | -.09 | ***-.32*** |
| **Object** | .07 | .19 | -.07 | .01 | ***.25*** | .01 |
| **Verbal** | -.09 | .03 | ***.27*** | -.05 | .04 | .20 |

*Note*. Number of items per scale: spatial 15, object 15, verbal 15. *R*-values of significant ($p$<.05 no correction for multiple testing) correlations are highlighted in bold-face, italic, and underlined (N=70).

I further inspected the correlations between each OSIVQ item and modality-specific abilities (see Table 4). Results revealed that only the items that ask for the self-report of an ability were significantly correlated with modality-specific abilities. There were three exceptions (OSIVQ 2, 12, and 25). However, exception 1 (OSIVQ 2) assessed a profession preference and exception 3 (OSIVQ 25) the preference of modern over non-modern art. Profession and art preferences may theoretically be related to modality-specific cognitive style but clearly do not directly assess it. Exception two (OSIVQ 12) satisfies content validity by asking for the nature of habitual internal images.

***Style and spontaneous thinking modality.*** From a theoretical perspective, there is no need for a strong association between the propensity to represent information in a particular modality and modality-specific abilities. The only requirement for object-visual style is that the individual experiences themselves as able to internally create detailed, realistic images; for spatial-visual style to create schematic, spatial images; and for verbal style to form verbalized thoughts (of any given level of sophistication).

However, we would expect style (habitual representation) to be correlated with spontaneous thinking modality during resting. It may also be related to thinking during the execution of cognitive tasks. However, the choice of thinking modality during tasks may be confounded by other factors such as perceived optimal modality selection for success in the task and flexibility in modality choice. We would expect moderate to strong correlations between style and thinking during resting of the same modality, and no correlations between different modalities.

I inspected correlation patterns of the OSIVQ. As expected, Pearson correlations between style and thinking modality during resting revealed consistent moderate to strong correlations for object-visual style. However, the correlation coefficients between spatial style and spatial thinking during resting were negative (though not significant); the correlation coefficients between verbal style and verbal thinking were positive but only significant for assessment time point 1. The strong positive correlation between object-visual style with spatial-visual thinking may indicate a problem of discriminant validity or a problem of spatial-visual thinking assessment.

*Table 5*

Pearson r-values of Correlations between Thinking Modality during Resting and OSIVQ-Assessed Object-Spatial-Verbal Cognitive Style

| | **OSIVQ 1** | | | **OSIVQ 2** | | |
|---|---|---|---|---|---|---|
| **Thinking** | **Spatial** | **Object** | **Verbal** | **Spatial** | **Object** | **Verbal** |
| **Spatial** | -.22 | ***<u>.67</u>*** | .01 | -.18 | ***<u>.65</u>*** | .02 |
| **Object** | -.06 | ***<u>.65</u>*** | -.21 | -.03 | ***<u>.55</u>*** | -.17 |
| **Verbal** | -.06 | -.22 | ***<u>.25</u>*** | -.09 | -.16 | .19 |
| **Abstract** | ***<u>.29</u>*** | -.11 | -.09 | .23* | -.03 | -.04 |

*Note*. R-values of significant (p<.05 no correction for multiple testing) correlations are highlighted in bold-face, italic, and underlined (N=68, 66).

***Style and brain electric activity.*** As discussed in detail in Manuscript 3, we would also expect correspondences between modalities and brain electric activity. Such correspondences were successfully induced by having participants execute modality-specific tasks, and by correlating EEG measures with MOTQ-assessed spatial-object-verbal style (see Manuscript 2 and 3).

I also investigated whether OSIVQ-assessed style would relate to brain electric activity.

Pearson correlations revealed no significant correlations (p>.05, uncorrected) between EEG microstates during resting and OISVQ assessed style (Table 6). However, there was a trend (p>.10) for verbal style to be negatively correlated with duration of microstate classes A and B. A negative significant association between verbal style and class A duration was retrieved via the MOTQ (Manuscript 2).

*Table 6*

Pearson r-values of Correlations between Microstate Parameters during Resting of the Four EEG Microstate Classes (A, B, C, D) with OSIVQ-Assessed Object-Spatial-Verbal Cognitive Style

| **Microstate Parameters** | **Modalities** | **OSIVQ assessed Style** | | | |
|---|---|---|---|---|---|
| | | **A** | **B** | **C** | **D** |
| | **Object-Visual** | .12 | .14 | .08 | -.09 |
| **Duration** | **Spatial-Visual** | .12 | .09 | .06 | .01 |
| | **Verbal** | -.25 | -.22 | -.13 | -.01 |
| | **Object-Visual** | -.03 | .04 | -.06 | -.13 |
| **Occurrence** | **Spatial-Visual** | -.11 | -.06 | -.12 | .08 |
| | **Verbal** | .11 | -.01 | .17 | .19 |
| | **Object-Visual** | .03 | .13 | .02 | -.13 |
| **Coverage** | **Spatial-Visual** | -.02 | -.01 | -.03 | .05 |
| | **Verbal** | .00 | -.13 | .00 | .09 |

*Note*. OSIVQ scale scores were averaged across the two assessment time points (except for the two participants where the second assessment was not available and no averaging was performed) (N=61).

Pearson correlations between OSIVQ-assessed style and the loadings of the nine independent components (ICs, retrieved as described in Manuscript 3) revealed significant associations across assessment time points and conditions (Table 7). The components most consistently associated with spatial-visual style were IC 3 (positive) and IC 4 (negative), and IC 2 (positive) for object-visual style. No IC was associated with verbal style.

The consistent correlations between IC 3 and 4 (as well as trends for 7, 8, 10, 12) with spatial-visual style are reminiscent of the correlations between the same ICs with spatial-visual ability (reported in Manuscript 3). The correlation between object-visual style and IC 2 were also observed for the MOTQ assessed object-visual style dimension (see Manuscript 3). Beyond, the relationships revealed by correlations with the OSIVQ, MOTQ-assessed cognitive style revealed a positive association between verbal style with IC 8.

In sum, for the spatial dimension, the pattern of correlations of OSIVQ-assessed style with independent brain networks was very similar to that observed for spatial ability in Manuscript 3. For the object-visual dimensions the associated brain network was the same as for the MOTQ. For the verbal dimension, no association was found for the OSIVQ.

*Table 7*

Pearson r-values of Correlations between OSIVQ-Assessed Cognitive Style with Independent Components

| | | | **Independent Component** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Scale | Cond | OSIVQ | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| Spatial | Re | 1 | -.16 | -.14 | **.34*** | **-.38*** | -.01 | -.11 | -.15 | **-.19** | .06 |
| | | 2 | -.16 | **-.20** | **.28*** | **-.39*** | -.02 | **-.24*** | **-.24*** | **-.20** | .08 |
| | Sv | 1 | -.13 | -.11 | **.28*** | **-.34*** | .02 | -.10 | **-.18** | **-.17** | .03 |
| | | 2 | -.14 | -.16 | **.23*** | **-.37*** | -.01 | **-.23*** | **-.27*** | **-.18** | .03 |
| | Ov | 1 | -.09 | -.09 | **.36*** | **-.30*** | .00 | -.09 | **-.18** | **-.17** | -.02 |
| | | 2 | -.11 | -.16 | **.32*** | **-.34*** | -.02 | **-.23*** | **-.26*** | **-.21** | .04 |
| | Ve | 1 | -.12 | -.09 | **.36*** | **-.33*** | -.01 | -.04 | -.15 | -.16 | -.05 |
| | | 2 | -.13 | -.14 | **.30*** | **-.36*** | -.04 | -.16 | **-.24*** | **-.20** | -.05 |
| Object | Re | 1 | .08 | **.23*** | -.05 | .07 | -.15 | **-.25** | .08 | .05 | -.04 |
| | | 2 | .05 | **.21** | .00 | .05 | -.14 | **-.18** | .06 | .06 | -.11 |
| | Sv | 1 | .10 | **.29*** | -.02 | .07 | -.13 | **-.18** | .04 | .00 | -.12 |
| | | 2 | .04 | **.26*** | -.01 | .05 | -.12 | -.15 | .04 | .04 | -.15 |
| | Ov | 1 | .09 | **.26*** | -.04 | .02 | -.15 | **-.19** | .06 | .03 | -.11 |
| | | 2 | .05 | **.23*** | -.03 | .02 | -.14 | -.17 | .05 | .08 | -.13 |
| | Ve | 1 | .10 | **.27*** | .00 | .06 | -.10 | -.13 | .05 | -.03 | -.15 |
| | | 2 | .05 | **.24*** | .05 | .04 | -.12 | -.10 | .05 | .00 | **-.18** |
| Verbal | Re | 1 | .02 | -.01 | -.10 | .15 | .05 | .07 | .08 | -.02 | -.05 |
| | | 2 | -.06 | -.04 | -.15 | .07 | .11 | .04 | .06 | -.07 | .00 |
| | Sv | 1 | -.04 | -.06 | -.10 | .10 | .02 | .05 | .07 | .04 | .04 |
| | | 2 | -.09 | -.05 | -.12 | .03 | .09 | .03 | .05 | -.03 | .04 |
| | Ov | 1 | -.08 | -.09 | -.16 | .10 | .07 | .04 | .05 | .08 | .07 |
| | | 2 | -.13 | -.10 | **-.20** | .02 | .12 | .00 | .04 | .02 | .09 |
| | Ve | 1 | -.02 | -.03 | -.11 | .15 | .06 | .01 | .07 | .07 | .07 |
| | | 2 | -.08 | -.06 | -.11 | .06 | .09 | -.05 | .06 | .03 | .15 |

*Note*. Correlation coefficients are reported separately for the two OSIVQ assessment time points (OSIVQ1: N=61, OSIVQ2: N=59) during four conditions: resting (Re), spatial visualization (Sv), object visualization (Ov), and verbalization (Ve). Bold, italic *p*<.20; *, underlined *p*<.10.

### 3.1.2 MOTQ.

***Validity***

Support for the validity of the MOTQ scales was provided in Manuscripts 1, 2, and 3. Manuscript 1 and 3 report correlations between style and EEG measures separately for the three MOTQ subscales (learning, habit, and ability). However, Manuscript 2 does not include separate subscale-wise correlations. The respective association between EEG microstate class parameters and verbal style may thus solely reflect the association between an EEG measure and self-reported ability rather than cognitive style.

A re-inspection of subscale-wise correlations reveals that this is not the case. The correlations with class A are of the same direction and significant (at least at trend level $p<.10$) for all subscales ($r$=-.28, -.21, -.30 for learning, habit, and ability respectively). The correlations with class C are also significant for the learning, and habit subscales and not the ability subscale ($r$=.29, .23, .15 for learning, habit, and ability respectively).

***Limitations of Visual-Verbal***

This thesis focuses on the investigation of visual and verbal thinking modalities. However, we report in Manuscript 1 that ten percent of the 468 participants of Data Assessment 2 scored below average on all three cognitive style dimensions. This finding indicates that some individuals may perceive their thoughts as neither primarily visual nor verbal.

The MOTQ contains three questions that attempt to explore such additional modality dimensions (see Dunn & Dunn, 1979 for a similar distinction). They ask respondents whether they perceive their thinking as dominated by abstract, auditory, or tactile information (see MOTQ items 37 through 39 in Manuscript 1).

Analyzing respondents' answers to these questions revealed that approximately 30% of participants consider themselves primarily abstract thinkers (neither visual nor verbal), 40% consider themselves auditory but not verbal (sensible to noise and sounds), and 30% consider themselves tactile (sensible to the way the environment feels). These percentages were very similar for the two samples of Data Assessment 1 and 2, and across the two assessment time points of each of these assessments (Table 8).

*Table 8*

Percentage of Participants Who Report themselves to be Abstract, Auditory, or Tactile Thinkers

| | MOTQ 1 | | | MOTQ 2 | | |
|---|---|---|---|---|---|---|
| | Abstract | Auditory | Tactile | Abstract | Auditory | Tactile |
| Assessment 2 | 34% | 45% | 34% | 29% | 38% | 30% |
| Assessment 3 | 30% | 46% | 30% | 25% | 38% | 28% |

*Note*. Participants were added to the percentage if they agreed or strongly agreed to the modality-specific statements (abstract, auditory, tactile) of the respective MOTQ items (Data Assessment 2: N = 468, 197, Data Assessment 3: N=70, 68 for MOTQ 1, and 2, respectively).

Auditory and tactile statements were not phrased to exclude visual and verbal thoughts. However, the abstract statement was. It appears noteworthy that almost a third of the investigated samples reportedly perceive their thinking as abstract. The nature of these abstract thoughts may represent a distinct category, different from visual and verbal. This distinct category may be reflected with a likewise distinct neural correlate.

After EEG recording runs, participants were asked to state their agreement to a number of statements related to their modality of thinking. This included the following statement: "Abstract Thinking: My thinking was primarily abstract (neither visual nor verbal)." They were asked to rate their agreement to this statement on a continuous rating scale ranging from 0 (not at all) to 100 (very much so). I considered ratings of 50 and higher as an indication for abstract thinking. According to this threshold, 21% rated their thinking as abstract during resting, 7% during spatial visualization, 4% during object visualization, and 12% during verbalization.

### 3.1.3 Object-Spatial-Visual Memory Test

Participants of Data Assessment 3 completed the Object-Spatial-Visual Memory Test after the EEG experiment. It assesses memory for spatial-visual and object-visual aspects separately.

On average, participants answered 75% of the 30 questions correctly (78% spatial, 72% object, N=70). The two scores for spatial- and object-visual aspects were not correlated ($r$=.01, $p$>.20). Only one participant was able to answer all questions correctly. I noted this and asked this participant after the experiment whether he felt that the questions had been too easy. He reported to have a photographic memory and could easily recall each image in great detail after it had been presented.

## 3.2 Electroencephalography

### 3.2.1 Spectral Analysis

I re-analyzed the electroencephalography (EEG) data obtained in data assessment 3. For each participant, each condition, each run, and each EEG channel, I computed the spectral power of the first five artifact-free two-second epochs. I averaged the retrieved spectra across epochs, across channels, and across runs. The retrieved mean spectra across participants are illustrated in Figure 3.

Before statistical analysis, I applied log-transformation to the spectra to obtain approximately normal distribution. Paired t-tests revealed significant ($p<.05$ uncorrected) differences between conditions. Spectral power was higher during resting compared to tasks. This power increase for resting was significant in all frequency bands when compared to visualization (Ov and Sv), and in alpha 1, alpha 2, beta 2, and beta 3 when compared to verbalization. EEG spectral power was higher during verbalization compared to visualization (Ov and Sv) in delta, theta, beta1, and gamma. No differences were found between the two visualization conditions.

These results are in line with previous studies which suggest that increased task demands are associated with decreased EEG alpha power (Klimesch, 1999). Furthermore, the shape of the spectral curve suggests that the quality of artifact-free EEG epochs was good. This is suggested by the clear peaks in the alpha bands and comparably low delta and gamma power.

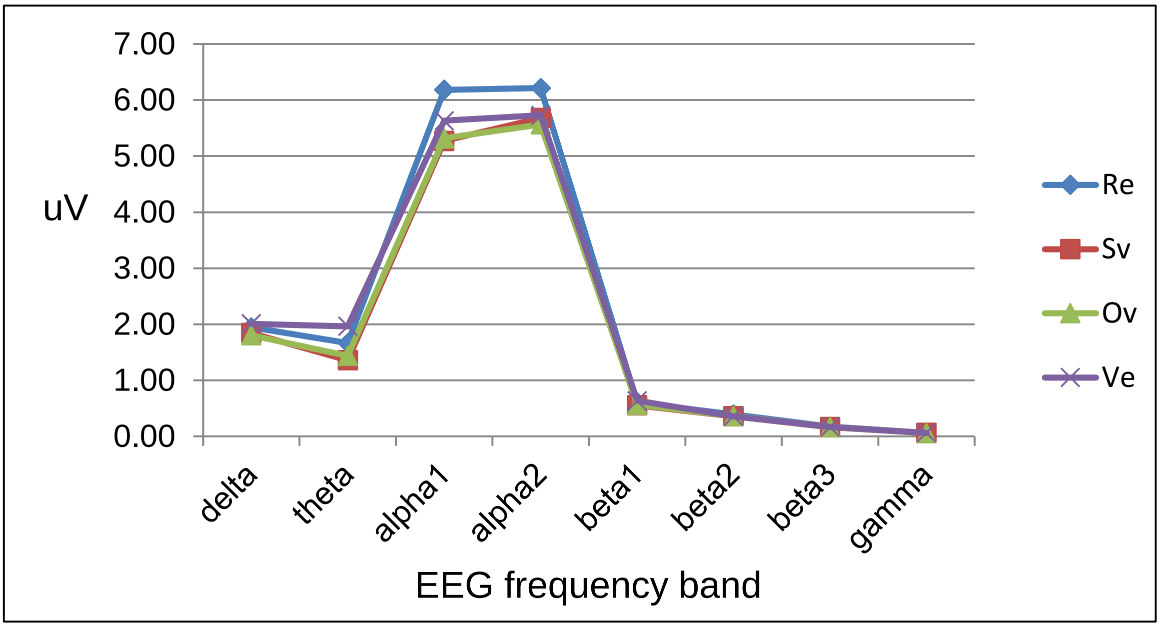


*Figure 3.* Mean EEG power spectra.

Mean EEG power spectra across participants for the four conditions resting (Re), spatial visualization (Sv), object visualization (Ov), and verbalization (Ve) (N=61).

# 4. Discussion

This thesis contributes to four fields related to brain electric mechanisms and modalities of thinking: (1) the assessment of modalities of thinking, (2) the investigation of interrelationships between modalities of thinking and related behavioral measures, (3) the analysis of brain electric mechanisms, and (4) the investigation of interrelationships between modalities of thinking and brain electric mechanisms.

## 4.1 Modality of Thinking Assessment

### 4.1.1 Previous Questionnaires

This thesis identified three major problems of previous self-report assessment measures of visual-verbal cognitive style: (1) they include items of questionable content and construct validity (see also for this criticism Antonietti & Giorgetti, 1992, 1998; Childers et al., 1985; Curry, 1983; Mayer & Massa, 2003), (2) they assess visual-verbal cognitive style based on an outdated bipolar model (see also for this criticism Antonietti & Giorgetti, 1992, 1998; Blazhenkova & Kozhevnikov, 2009; Edwards & Wilkins, 1981; McGrath et al., 1989; Paivio & Harshman, 1983), and (3) they lack a distinction between the spatial- and object-visual dimension (see also for this criticism Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009; Hegarty & Kozhevnikov, 1999).

The identification of these problems is not new. However, since they have never been considered simultaneously, all previous measures suffer from at least one. A measure which had not been previously criticized, is the Object-Spatial Imagery and Verbal Questionnaire (OSIVQ: Blazhenkova & Kozhevnikov, 2009). It suffers from problems (1) and (2). Several assessments of the OSIVQ were conducted as part of this thesis (see Data Assessments 2, 3). The results of the respective analyses are described in Manuscript 1 and in Unpublished Results. They support previous findings which suggested that the OSIVQ is reliable (high internal consistency and short-term re-test reliability: Blazhenkova & Kozhevnikov, 2009).

However, high reliability is of limited use when an instrument is not valid, i.e. does not measure what it intends to measure (Amelang & Schmidt-Atzert, 2006). The OSIVQ suffers from such a (1) lack of validity. This problem was identified based on its numerous items which measure concepts related to but distinct from visual-verbal cognitive style[18]. These items measure various constructs including profession preferences, enjoyment of modality-related activities, and ability self-reports (see also Manuscript 1). The ability self-reports concern the largest item number, namely 14 of the 45 OSIVQ items. Statistical analyses revealed the problematic effect of these items. They lead to a strong overestimation of the interrelationship between visual-verbal cognitive style and objectively assessed modality-specific abilities. Furthermore, they may also lead to an overestimation of the stability of visual-verbal cognitive style. Whether modality-specific styles or abilities are more stable is an empirical question. However, at least for retrospective ability self-reports (e.g. remembered success as a pupil) which are also included in the OSIVQ, no changes in responses across time would be expected (unless the respondents' memory changes). Thus, these items undermine the questionnaire's ability to identify potential visual-verbal cognitive style changes across time.

The OSIVQ also suffers from problem (2), the lack of assessment of the three dimensions on independent unipolar scales. This is surprising given that the OSIVQ was built on the spatial-object-verbal cognitive style model that emphasizes the significance of unipolar assessment. However, 14 of the 45 OSIVQ items ask respondents to choose between two dimensions. The respective responses are then arbitrarily attributed to only one of the two scales. Statistical analyses again revealed the problematic effect of these items. They lead to strong negative loadings on the factor of the competing dimension, negative correlations between the three scales, and strong negative correlations with external variables. For example, the OSIVQ verbal scale does not correlate with verbal ability but it correlates consistently across assessment time points with spatial ability (negative correlations). These negative correlations may be indicative of construct-irrelevant variance.

Arguably, these negative correlations may be valid and not artifacts of the bipolar items. For at least two reasons, I believe this to be unlikely. Firstly, the items affected by high negative loadings on an undesired factor were limited to the items that forced respondents to choose between two dimensions. Secondly, the Modality of

[18] In line with the previous literature and the definition of "cognitive" and "style", visual-verbal cognitive style was defined as the propensity to represent information in an object-, spatial-visual, or verbal format. It is distinguished from self-reported ability, learning style, and learning preferences.

Thinking Questionnaire (MOTQ), which refrains from using dichotomous items, showed no strong negative loadings on undesired factors.

Artificial negative loadings are particularly problematic when the population aimed to be investigated does not show a clear preference[20] of one dimension over the others. The cluster analysis of the MOTQ suggests that this is the case. Sixty percent of participants do not report high scores on one and low scores on the other dimensions but any other combination between high and low scores. The application of dichotomous items would at least bias this retrieved empirical distribution since individuals who apply two styles equally can only resort to the middle category of the Likert scale to express their lack of preference[20]. Middle category answers provide no information on whether both styles are used equally strongly or equally little.

Arguably, dichotomous items may be necessary for respondents to grasp the distinction between the two visual dimensions.[19] This is a theoretical possibility and warrants further study. However, the results of the MOTQ-based cluster analysis suggest that at least 52% of individuals in our student sample were able to distinguish between the two dimension as reflected by their high score on one and low score on the other dimension. The remaining 48% scored high (30%) or low (18%) on both visual dimensions. It can only be speculated whether they had distinction difficulties or simply dis- / preferred[20] the verbalization over the two visualization dimensions or had no propensity towards any dimension.

### 4.1.2 The Modality of Thinking Questionnaire

This thesis includes its own contribution to the assessment of visual-verbal cognitive style. As described in Manuscript 1, we developed a new questionnaire, the Modality of Thinking Questionnaire (MOTQ). It comprises three scales to assess the three dimensions spatial visualization, object visualization, and verbalization. Each of these scales comprises three subscales of identical item number that assess modality-

[19] This argument could justify the integration of the 8 of the 14 dichotomous items that contrast object-visual from spatial-visual but not the 6 items that contrast visual from verbal.

[20] Preferred is here used for ease of formulation to refer to a cognitive style, ability-self report, and learning style, not a preference in the sense of liking or enjoyment as distinguished in Introduction.

specific learning style[21], modality-specific cognitive style, and modality-specific ability. All subscales measure what they intend to measure, use unipolar scales, and the visual-modality related items all refer to either only spatial- or only object-visual properties.

The original conception of the MOTQ interpreted the scores of the three scales as a measure of spatial-object-verbal cognitive style. This is in line with the previous style questionnaires which included ability self-reports and questions related to learning style and preferences (e.g. Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009; A. Richardson, 1977). It is also in line with a recent review which questions the necessity for a distinction between cognitive style and learning style (Kozhevnikov et al., 2014). However, various previous reports and findings, as well as results from this thesis, illustrate the drawbacks of this lack of conceptual distinction.

Consequently, I concluded that I needed to revise the original conceptualization of the MOTQ. The scales of the MOTQ assess a heterogeneous construct including the ability to acquire, the habit to represent, and the ability to process information in a particular modality. Several analyses described in Manuscripts 1 to 3 used the scores of these scales and interpreted their associations based on the old conceptualization. This may be problematic since the respective associations may not relate to style but be limited or at least driven by any of the other two subscales. To avoid misinterpretations, I recomputed the respective correlations for the separate subscales. Results revealed that all reported findings with brain electric mechanisms were related to style and not solely driven by ability self-reports or learning style. There was one exception. Objectively assessed verbal ability was not significantly correlated with verbal style (based on the style-related habit subscale of the MOTQ). Therefore, the respective significant result of the sum scale cannot be interpreted as a significant association between verbal style and ability.

The subscales of the MOTQ are of agreeable internal and high re-test reliability but very short (four items each). Future research should consider extending these subscales to further increase their reliability and thus maximal possible validity. For

[21] As described in Introduction, learning style refers to the (self-reported) ability or efficiency to learn with material of the three modalities. It is distinguished from learning preference which refers to an individual's preference to learn from material of various modalities.

these extended scales, validation for separate use would also be beneficial. This could avoid lengthy testing when only cognitive style, ability self-report, or learning style are aimed to be assessed.

This thesis also includes the development of an object-spatial-visual memory test (OSVMT). Preliminary results were reported in Unpublished Results. They suggest that the OSVMT may be a promising measure to assess spatial- and object-visual memory. However, future work must investigate the reliability and validity of the OSVMT and its relationship with other modality-related measures.

### 4.1.3 Beyond Visual-Verbal

As described in Unpublished Results, individuals might use internal representations that are neither visual nor verbal. At least two results support this hypothesis. First, 21% percent of participants described their thinking during resting as abstract rather than visual or verbal[22] (based on Data Assessment 3). Second, approximately a third of participants considered their thinking primarily abstract rather than visual or verbal based on their answer to a respective item in the MOTQ (based on Data Assessment 2). Thoughts that are perceived as abstract may relate to a separate internal representation modality with its own neural correlate. Future studies must investigate this possibility.

## 4.2 Behavioral Measures Interrelationships

The findings described in Manuscript 1 and Unpublished results revealed associations between visual-verbal cognitive style with gender, degree paths, spontaneous thinking modality, and modality-specific abilities. Style-related gender and degree path differences are described in detail and discussed in Manuscript 1.

Correlations between modality-specific abilities revealed consistent associations with style for the spatial- and object-visual modality but not for the verbal modality. Associations of the object-visual dimension were limited to self-report

[22] This number is derived from participants' mean responses after the resting runs of the EEG recording to the following statement: "Abstract Thinking: My thinking was primarily abstract (neither visual nor verbal)." They rated their agreement to the statement on a continuous rating scale ranging from 0 (not at all) to 100 (very much so). Ratings greater than 50 qualified as abstract thinking reports and were used for the percentage computation.

measures. These results agree with a hypothesis formulated in Introduction. If an individual lacks the ability to form spatial- or object- visual images, they can hardly be expected to be capable of doing so habitually. Furthermore, associations between style and ability may be mutually reinforced. High modality-specific abilities may encourage the representation and processing in the respective modality and vice-versa. High abilities may originate from frequent representation and processing and underlying differences in modality-specific neural networks. Frequent representation and processing may originate and / or trigger strengthening of modality-specific synaptic pathways and thus increase modality-related neural efficiency (see Manuscript 3). Longitudinal studies are needed to verify or discredit these speculations.

Object-visual style was only significantly associated with object-visual ability if assessed via self-reports but not cognitive tests. I suspect this is due to the different constructs measured by the two. The used self-report measure assesses an individual's ability to create detailed, realistic internal images (Marks, 1973). The used cognitive tests measure the success of individuals in identifying objects in distorted images and label them (e.g. Ekstrom, French, Harman, & Derman, 1976; Horn, 1962). Both measures were previously used to assess object-visual ability (Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009). However, results suggest that object-visual style is related to the ability to form detailed, realistic internal images only. No evidence was found that it is also related to the ability to identify objects in distorted images and label them (see also Manuscript 3). The lack of association with the latter is not surprising. It is unclear why an individual who habitually creates detailed, realistic internal images would need to be faster or better at object identification. Especially, since object identification tests often involve schematic rather than detailed depictions of objects and reward speed of verbalization. These properties suggest that spatial-visual abilities and verbal abilities are also involved.

Verbal style was not consistently correlated with verbal abilities. I suspect that this lack of correlation is due to the fact that the only prerequisite to frequently internally verbalize is the ability to speak internally. There is no necessity for an individual to excel in speaking, writing, or vocabulary to be able to do so. However, the latter is what verbal ability tests measure.

Spatial-, object- visual, and verbal style were associated with spontaneous thinking modality. However, the associations for the spatial-visual dimension were not consistent for resting across assessment time points. One possible explanation is that the question used to ask about spontaneous spatial-visual thinking fell short to comprehensively capture the concept in question. The participants answered whether their thinking "was comprised of images depicting spatial relations between objects." Therefore, it failed to specify the image quality which is schematic / low-resolution and decisive for the distinction between spatial-visual and object-visual style. Another possible explanation may be that spatial visualizers use spatial-visual thinking habitually to solve problems but not at rest (for example when they need to orient themselves in space or solve mathematical problems; see also Hegarty & Kozhevnikov, 1999; Presmeg, 1986). Furthermore, participants who scored high on the spatial-visual style scale tended to describe their thinking during resting as abstract rather than visual or verbal. Previous studies report that spatial imagery must not rely on the visual modality but could also be auditory or tactile (e.g. Kozhevnikov, Hegarty, & Mayer, 2002). Possibly, participants referred to the abstract category to express that their thoughts may have been spatial but not visual. These aspects were not considered in this thesis and warrant further study.

### 4.3 Analysis of Brain Electric Mechanisms

This thesis contributes to the analysis of brain electric mechanisms with the development of the *keypy* EEG Library. The library allows the computation of EEG microstates from artifact-free data. It includes functions for the necessary preprocessing and subsequent statistical analyses. The library is written in the Python program language and is freely available under the open source license GPL Clause-3 on https://github.com/keyinst/keypy. It complements existing software solutions by providing an efficient computation framework that is fully scriptable and does not rely on user-interaction via graphical user interfaces.

### 4.4 Brain Electric Mechanisms and Modalities of Thinking

The results of this thesis suggest that modalities of thinking are reflected in brain electric mechanisms. Relationships were revealed between four modality-related measures, namely spontaneous self-reported thinking modality, induced thinking modality, spatial-object-verbal cognitive style, and modality-specific abilities with three measures of brain electric mechanisms: spectral power, EEG microstates, and eLORETA cross-frequency networks.

### 4.4.1 Spectral Power

Mean power spectra across channels and epochs revealed a significant effect of task-induced modalities of thinking on brain electric activity (see Unpublished Results). Alpha power was higher during resting than tasks (spatial visualization, object visualization, and verbalization). This result agrees with the extensive EEG literature that reports a negative association between modality-specific task demands and alpha power (Pfurtscheller, 2003; Tiihonen et al., 1991). Results also revealed spectral power differences between visualization and verbalization. However, their interpretation is difficult due to a lack of information of the specific EEG channels or cortical sources that contributed this effect.

### 4.4.2 EEG Microstates

The EEG microstate results are described and discussed in detail in Manuscript 2. The main finding is the effect of task-induced modalities of thinking on three EEG microstate parameters: duration, occurrence, and coverage. These parameters increased for microstate class A during visualization and class B during verbalization. These results were interpreted by taking into account two aspects: (1) the frequency range that contributes most strongly to the EEG microstates, which is the alpha band, and (2) the primary cortical sources of microstate classes A and B, which are in the left and right posterior-occipital cortex. Since posterior-occipital alpha primarily exhibits inhibitory rather than excitatory functions (Pfurtscheller, 2003), increases in EEG microstate class parameters may likewise reflect increased inhibition. Consequently, parameter increases in classes A vs. B would reflect decreased left- vs. right-posterior cortical activity. This pattern is in line with previous results in which left and right posterior activity were associated with verbal and visuo-spatial processing, respectively (Buchsbaum, Hickok, & Humphries, 2001; Malhotra, Coulthard, & Husain, 2009; Newcombe, Ratcliff, & Damasio, 1987; Vigneau et al., 2006; Weiss et al., 2006).

Despite the extensive literature on EEG microstates in health and pathology (e.g. Andreou et al., 2014; Koenig et al., 2002; Lehmann, Faber, Galderisi, Herrmann, Kinoshita, Koukkou, Mucci, Pascual-Marqui, Saito, & Wackermann, 2005; Strik et al., 1997), to my knowledge, the possibility that the EEG microstates may reflect primarily inhibitory activity has not been considered. The study that identified their cortical sources and their effective connectivity (Pascual-Marqui et al., 2014), and the study that revealed no associations with EEG frequency bands (Britz et al., 2010) await replication.

Despite the significant effects of the visual and verbal tasks on EEG microstate parameters, the magnitude of effects was small. Moreover, all EEG microstate classes were observed during all conditions. Consequently, a simple association of an EEG microstate class with a single function such as visual or verbal processing appears very unlikely. The investigation of their interplay via the analysis of their sequence (Gärtner et al., 2015; Gschwind, Michel, & Van De Ville, 2015) may shed more light on their physiological functions.

Another interesting finding is the strong person specificity of the EEG microstate parameters. For example, an individual with comparably long class A microstates during resting also exhibits long class A microstates during tasks. High person specificity was also reported for other EEG parameters (Buckelmüller, Landolt, Stassen, & Achermann, 2006; Poulos, Rangoussi, Chrissikopoulos, & Evangelou, 1999). We investigated whether this person specificity was associated with person parameters related to modalities of thinking. Pearson correlations revealed a negative association between verbal cognitive style and microstate class A, and a positive association with class C. However, these were two singular significant correlations from a large number of correlations that were not corrected for multiple testing. Different modality-related parameters or modality-unrelated parameters may account for the strong person-specifity of the EEG microstate.

### 4.4.3 EEG eLORETA Cross-Frequency Networks

The EEG eLORETA cross-frequency network results are described and discussed in detail in Manuscript 3. The main finding distinguishes state effects from trait effects[23]. State effects were induced via visual and verbal tasks. They led to increased activity in particular brain networks. These networks had in common that they all included alpha decreases in modality-specific and alpha increases in areas of competing modalities. Trait effects were investigated via correlations with modality-related person parameters. They were also associated with particular brain networks.

[23] The term trait effects, for associations between person parameters and networks, is used for reasons of simplicity. It refers to results from correlational analyses from which no information on causality can be retrieved.

They also had something in common, namely that they included alpha increases in modality-specific and alpha decreases in areas of competing modalities.

The reported state effects are in agreement with the extensive literature that suggests inhibitory functions of alpha oscillations in modality-specific regions when induced via tasks (Pfurtscheller, 2003; Tiihonen et al., 1991). The latter trait effects were related to previous reports in which increased modality-specific abilities were associated with increased neural efficiency in the respective cortical regions (Neubauer, Grabner, Fink, & Neuper, 2005). They may reflect increased automated processing induced by synaptic plasticity triggered by extensive use.

The statistical analysis of trait effects on brain networks suffer from a limitation. The significance thresholds applied could be considered too liberal. Correlational analyses relied on consistent associations across conditions and assessment time points at trend level (not corrected for multiple testing). Given the large number of analyses, rigorous multiple testing procedures would hardly have revealed any remaining significant results. To reduce the number of tests, averages could have been computed across conditions and assessment time points. Alternative statistical procedures such as linear mixed regression models could also have been considered. However, I decided to still report detailed results to maximize transparency in the degree and consistency (or a lack thereof) of effects and associations across conditions and assessment time points. Future hypothesis-driven studies are needed to replicate the reported pattern.

### 4.4.4 Limitations of the EEG Experiment

The experimental design of the EEG experiment (Data Assessment 3) is also associated with a number of limitations. These limitations concern results from Manuscripts 2 and Manuscript 3 since they relied on the same data assessment.

First, the design is cross-sectional and thus the data obtained do not allow to draw conclusions on the causal direction between style, ability, and activity in brain networks. The simple solution for this limitation would be to conduct an additional longitudinal study that examines reciprocal long-term effects of style, ability, and activity in brain networks.

Second, several limitations relate to the tasks used to induce visual and verbal processing. During visualization tasks, participants internally visualized a previously presented image (photographs for object visualization and schematic configurations of dots for spatial visualization). During the verbalization task, they internally verbalized the definition of an abstract noun. The reported behavioral and EEG results suggest that these tasks succeeded in inducing increased visual and verbal processing.

However, the differences between tasks were not limited to processing modality. At least two additional differences may have affected results. The first concerns the types of tasks used. The two visual tasks were imagery tasks, whereas the verbal task was a sentence generation tasks. Imagery tasks reportedly show common deviations from control conditions regardless of the particular modality (Daselaar et al., 2010). A modality-unrelated imagery network may thus have contributed to visual and verbal task differences. The second difference concerns the type of memory primarily involved. The two visual tasks primarily rely on short-term memory because they demand the recall of a previously presented image for internal reconstruction. The verbal task primarily relies on long-term memory because it demands the search for learnt associations with the noun to be defined.

The solution for these task-related limitations may be to use either imagery tasks only (including verbal imagery) or to use generation tasks only (including visual generation). Possible imagery tasks could ask participants to reiterate or reconstruct a series of images or words rather than just one. However, such singular or iterative imagery tasks are quite distinct from spontaneous internal visual and verbalizations and thus might negatively affect external validity. Another option would be to refrain from using imagery tasks altogether by using generation tasks only. However, when generation tasks are used for visual imagery, close attention needs to be paid to avoid inducing (visual) motor imagery. Otherwise an additional motor-imagery-only task would be required to be able to distinguish motor effects from visual effects. Several types of visual and non-visual motor imagery are distinguished and would demand consideration for inclusion. However, their exhaustive inclusion may render the experimental design increasingly long and complex.

Third, the time period during which participants executed the tasks may also have affected results. In our study, this was 50 seconds. Fifty seconds were perceived as an adequate time period to retrieve a verbal definition for a noun but the same time period was perceived as rather long to keep reproducing the same internal image.[24] To

[24] Prior to submitting Manuscript 2, I verified that the same result pattern would be retrieved when various parameters were modified. These analyses included the re-computation of all EEG microstate parameters

solve this problem, the time period of the whole task could be reduced. The associated reduction of the number of available EEG segments for analysis could be compensated by increasing the number of runs.

Despite the limitations of these tasks, significant differences between conditions concerned several brain areas and pathways primarily associated with visual and verbal processing. Thus, it is at least very likely that they reflect the intended differences in processing modality. Other areas related to memory and attention were also involved and interpreted accordingly.

However, the EEG measures used did not distinguish between the two visualization tasks. This was unexpected, since self-reported thinking modalities during conditions confirmed the successful induction of increased spatial-visual and object-visual processing. Moreover, according to the literature reviewed in Introduction, different brain networks are associated with spatial-visual and object-visual styles. Other tasks may prove more successful at revealing a distinction between spatial- and object-visual processing. However, a complete double dissociation between spatial and object visualization is hardly possible. Each conceivable spatial-visualization task will involve object-visual elements such as objects with a particular size, shape, and color, regardless of how simple or schematic they might be. Likewise, each conceivable object-visualization task will involve spatial-visual elements, at least spatial relations between objects or elements of objects.

Beyond limitations, several additional investigations await exploration. Interaction effects between spatial-object-verbal style and tasks on cross-frequency brain networks could be examined. This examination could possibly contribute to the evaluation of the recent conversion hypothesis that suggests that individual's process information in their preferred modality regardless of stimulus modality (Kraemer et al., 2014; Kraemer et al., 2009). Moreover, the possibility of predicting visual and verbal thinking within the same individual could be envisioned by using a classification algorithm. Thereby, EEG retrieved-measures from the first half (time-wise) of the recording could be used to predict and validate a second half of the recordings. I already investigated the possibility to predict style based on EEG measures derived from task-

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for the first 10 seconds of EEG only rather than the whole 50 second period, and in sum suggested that the reported findings are very robust.

induced modality-related differences. However, these investigations were not successful (results not reported in this thesis).

Finally, the sample of the EEG experiment (Data Assessment 3) was limited to healthy, right-handed, male students between 18 and 34. Future studies must resolve whether similar results can be retrieved from other populations.

### 4.5 Conclusion

This thesis identified major problems in previous self-report measures of visual-verbal cognitive style. The literature review revealed that these problems had been identified previously but never addressed together (e.g. Antonietti & Giorgetti, 1992; Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009; Mayer & Massa, 2003). The effects of these problems were illustrated based on a thorough analysis of the OSIVQ (Blazhenkova & Kozhevnikov, 2009), the state-of-the-art measure of visual-verbal cognitive style, being the only assessment that distinguishes between spatial and object visualization.

To remedy these problems, a new questionnaire was developed which comprises three scales that assess spatial visualization, object visualization, and verbalization. Each of these scales comprises three subscales that assess learning style, visual-verbal cognitive style, and self-reported ability. The scales revealed very satisfactory factorial structure, high internal and retest reliability, and associations with external measures including objectively-assessed modality-specific abilities, self-reported spontaneous and induced thinking. They also revealed different distributions in groups of reportedly different modality-specific preferences and abilities (gender, degree programs). Finally, their associations with brain electric activity also supported their congruent and discriminant validity.

Future studies could extend the subscales to facilitate their independent application and to further increase their reliability and thus their upper limit of validity. A valid assessment of visual-verbal cognitive style may not only be useful in basic research but also applied fields such as, business and management, and education in which cognitive style assessments are very popular (Armstrong et al., 2012; Kozhevnikov et al., 2014).

An assessment measure's validity is a prerequisite to the investigation of any interrelations of the construct with external measures of interest. Only when the development of a valid instrument is achieved will it be possible to draw final conclusions on the major questions of the field of visual-verbal cognitive style. They include the validity of the matching hypothesis (Pashler et al., 2008), the conversion hypothesis (Kraemer, Hamilton, Messing, DeSantis, & Thompson-Schill, 2014; Kraemer et al., 2009), the stability and / or trainability of visual-verbal cognitive style, and its associations with profession-relevant abilities.

The associations between modality-related person parameters and brain electric mechanisms revealed that indeed modalities of thinking are reflected in the brain and can be detected via EEG measured brain electric activity. The revelation of such interrelations is not new (e.g. Gevins & Smith, 2000; Lehmann et al., 2010). However, this thesis extended previous findings by revealing modality-related state and trait effects on EEG microstate parameters and topographies, and the activity in intra-cortical cross-frequency brain networks.

The obtained results suggest that the four EEG microstate classes (Koenig et al., 2002) may primarily reflect inhibitory rather than excitatory neural activity. Future studies must validate this hypothesis and further investigate the neural basis of the four EEG microstate classes.

The obtained results also suggested that modality-related state effects induce activity in particular brain networks. They were characterized by decreased alpha oscillations in modality-specific and increased alpha in areas of competing modalities. The inverse relationship was observed for associations with modality-related traits. The respective changes were associated with different functions of state-dependent and trait-dependent alpha. Future studies must reveal the consistency of the decomposed networks, their associations, and whether they can be extended to other modalities such as somatosensory and motor processing.

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7. Curriculum Vitae

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## Employment

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| 8/2009 – now | Research Assistant,<br>The KEY Institute for Brain-Mind Research, Zurich |
| 3/2009 – 8/2009 | Clinical Internship,<br>Psychiatrische Klinik Münsterlingen, Thurgau |
| 2/2009 – 6/2009<br>2/2008 – 6/2008 | EEG Tutoring, Department for Psychopathology and Clinical Intervention, University of Zurich |
| 12/2007 – 12/2008 | Research Internship Neuropsychology, Institute for Pharmacology and Toxicology, University of Zurich |
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## Education

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| 2012 – now | Structured PhD Program in Psychology,<br>University of Zurich |
| 2011 – now | International PhD Program in Neuroscience,<br>University of Zurich and ETH Zurich |
| 2005 – 2011 | Licentiate in Psychology (Grade Ø 5.875),<br>Psychopathology (Grade 6), and English Literature (Grade 6), Thesis on Brain Electric Mechanisms of Body- and Mind-Oriented Attention (Grade 6),<br>University of Zurich |
| 1999 – 2005 | Matura Profile: Modern languages (Italian, English) – Grade Ø 5.2,<br>Kantonsschule Rychenberg, Winterthur |
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| 2011 | Licentiate in Psychology, Psychopathology, and English Literature,<br>University of Zurich |

## Membership in Scientific Societies

| | |
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| 2012 - now | Member of the Swiss Society for Neuroscience |
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| 7/2007 – 12/2007 | Student Exchange Organization Committee, University of Zurich |
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## Languages and additional Skills

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| Languages | German (Native Language), English (Cambridge Certificate of Proficiency in English), French, Italian |
| Software Development | Lady Cycle: Menstrual Cycle Smartphone Application<br>keypy: Open Source Library for EEG data analysis |
| Programming | Python, Matlab, C++ |
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| Personal Interests | Travelling, Music (Piano, Dancing) |

## Articles in Peer Reviewed Journals

Faber, P. L., **Milz, P.**, & Lehmann, D. (2015). EEG of two persons during their roles as spiritual trance healer and as client – a pilot study. *Human Cognitive Neurophysiology*, 23.

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**Milz, P.**, Faber, P. L., Lehmann, D. (2013). EEG spectral power affected by meditation: a longitudinal case study. – Presented at the ZNZ Annual Meeting in Zurich, Switzerland, September 13, 2013. Abstract Book Page 62.

Painold, A., Reininghaus, E. Z., **Milz, P.**, Faber, P. L., Lackner, N., Bengesser, S., Letmaier, M., Holl, A. K., Lehmann, D., Kapfhammer, H-P. (2013). Increased frontal theta during depression compared to mania – an intra-individual source localization study. – Presented at the ZNZ Annual Meeting in Zurich, Switzerland, September 13, 2013. Abstract Book Page 70.

Painold, A., **Milz, P.**, Kapfhammer, H-P., Pieber, T., Lerchbaum, E., Obermayer-Pietsch, B. (2012). Disturbed eating behavior and its influences on the quality of life in polycystic ovary syndrome. *Journal für Klinische Endokrinologie und Stoffwechsel*: 5(S 3), 94. – Presented at the 15th Congress of the European Neuroendocrine Association in Vienna, Austria, September 12-15, 2012.

Painold, A., **Milz, P.**, Faber, P. L., Anderer, P., Letmaier, M., Holl, A. K., Saletu, B., Kapfhammer, H-P., Kochi, K., Lehmann, D. (2012). Functional network disruption in Huntington's disease. – Presented at the 16th International Congress of Parkinson's Disease and Movement Disorders in Dublin, Ireland, June 17- 21, 2012.

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